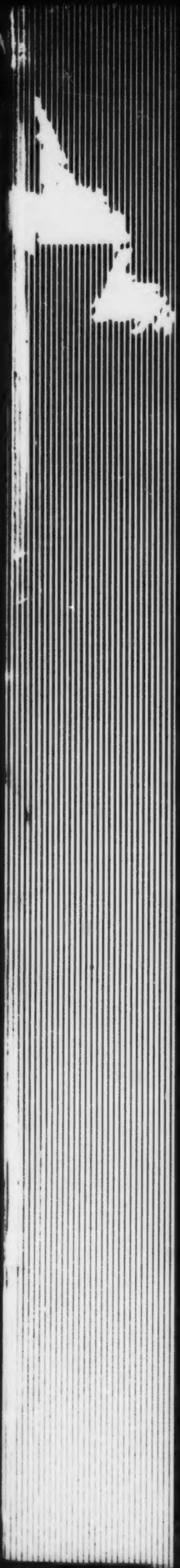

GEOLOGICAL SURVEY BRANCH
DEPARTMENT OF MINES AND ENERGY
GOVERNMENT OF NEWFOUNDLAND AND LABRADOR

CURRENT RESEARCH

REPORT 91 – 1

Compiled and Edited by
C.P.G. Pereira, D.G. Walsh and R.F. Blackwood

St. John's, Newfoundland
March, 1991

Geological Survey Branch
Department of Mines and Energy
Government of Newfoundland and Labrador

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PREFACE

This publication presents the preliminary results of the 1990 research program of the Geological Survey Branch of the Newfoundland Department of Mines and Energy. The 1990 program comprised some thirty projects, about half of which included a field component.

Major results of the program include the publication of a new geological map of Newfoundland, the first since 1967; release of the first surficial-geology map for the Island; identification of a number of industrial-mineral deposits, including deposits to meet the requirements of the Hibernia project for mineral aggregate; production of a new aeromagnetic datafile for Newfoundland for use with image-analysis software; and release of the first geochemical atlas for the province.

A new federal–provincial minerals agreement, the Canada–Newfoundland Cooperation Agreement on Mineral Development, was signed in September, 1990. The new agreement provides 17.5-million dollars for mineral-development activities in the province for the period 1991-1995. Approximately half of the total expenditure will be on geoscience, the remainder on mining technology, mineral economics, and direct assistance to the mineral industry. The provincial geoscience program, which has been operating at a reduced level since the end of the last agreement in 1989, will therefore see a significant increase in 1991.

B.A. Greene
Assistant Deputy Minister
Geological Survey Branch

Any reader who would like to write a rebuttal to, or discussion of, any report contained in this volume is invited to submit it to the editor by November 1, 1991, to be considered for inclusion in Report 92–1.

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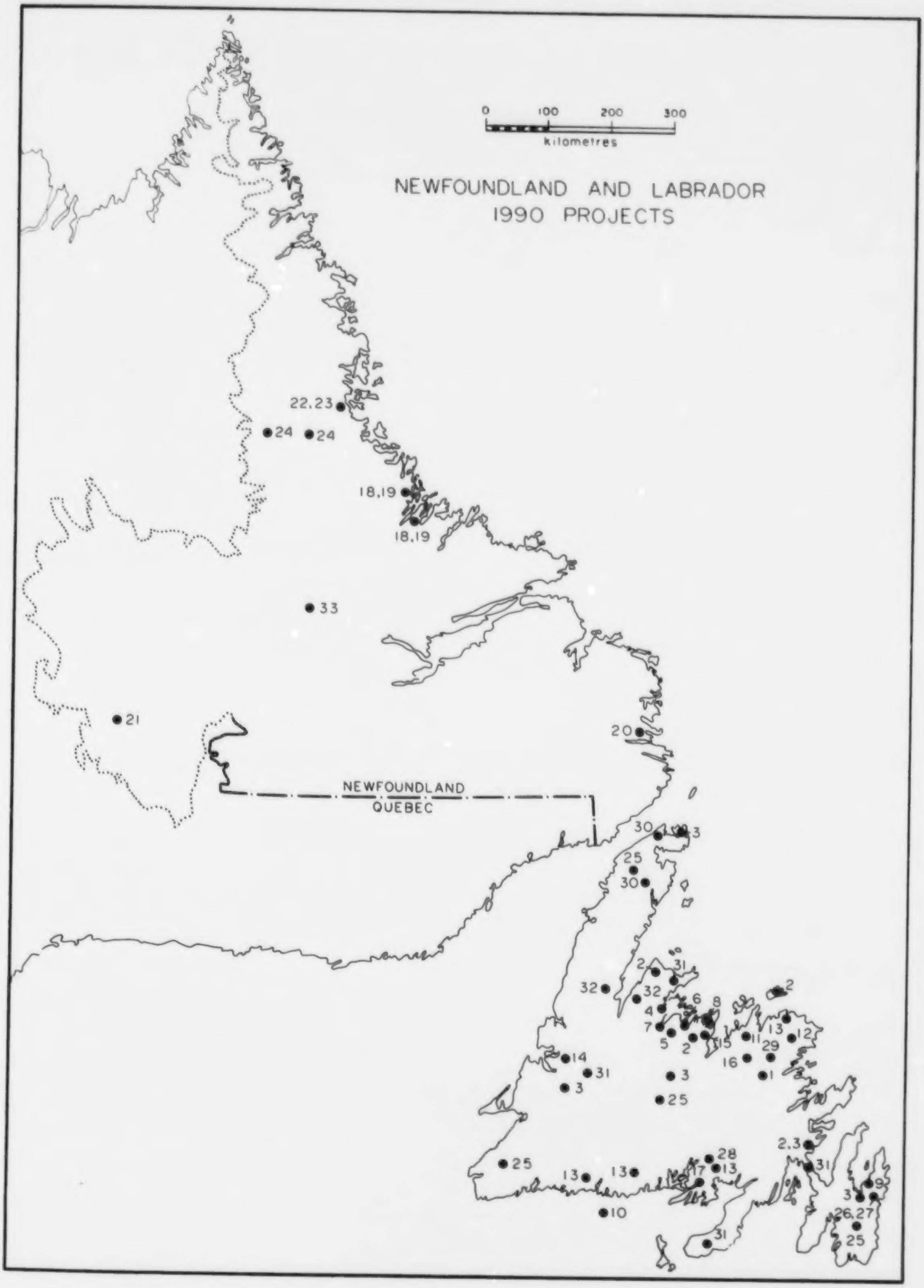

NEWFOUNDLAND AND LABRADOR
1990 PROJECTS

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Geological Survey Branch, Report 91-1, pages 1-12*

QUATERNARY GEOLOGY OF THE GANDER (NTS 2D/15) MAP AREA

Martin J. Batterson and Spencer Vatcher
Terrain Sciences Section

ABSTRACT

The Gander area of central Newfoundland has been affected by at least two ice-flow events. The first was eastward, from a source to the west of Mount Peyton; it formed striae and dispersed sediment eastward. In particular, clasts from the Mount Peyton intrusive suite are common across the study area. The second sediment-moving phase of ice flowed north to north-northeastward from a source in the Middle Ridge area, as shown by striations overprinting those of the last flow, by clast provenance and clast fabric data.

Diamictons are the most common sediment type found. They have a sandy matrix, containing 30 to 60 percent clasts, are moderately compact, and are massive, although small moderately to well-sorted sand and granule gravel lenses are common, especially beneath clasts. This sediment was probably deposited by basal melt-out processes. A veneer of clast-rich diamicton is common, and probably represents supraglacial meltout till. Valleys are commonly filled with glaciofluvial outwash sediments, up to 60 m higher than present river levels in the Southwest Gander River valley. These were deposited during deglaciation, and have been partially reworked into modern alluvial and deltaic deposits. In the area of The Outflow, laminated silt and clay sediments indicate a proglacial lake or marine incursion that extended up to 40 m above the present level of Gander Lake. Modern Gander Lake, to the east, may have been filled by ice at this time, effectively blocking the inferred major pre-glacial drainage system at the eastern end of the lake, routing drainage into the modern Gander River valley. Postglacial sediments include colluvial deposits at the base of steeper slopes, and bog deposits, which are common in poorly drained areas.

Subglacial meltout till is a suitable sampling media for drift exploration. Supraglacial meltout till, glaciofluvial and colluvial sediments, if sampled, should be considered separately because of their differing transport and depositional histories. Most sediments have a sandy matrix and are, therefore, permeable. Care should be taken when placing waste-disposal sites within these sediments to avoid potential groundwater or surface water contamination. Zoning of aggregate deposits identified within the area should also be implemented to allow their extraction.

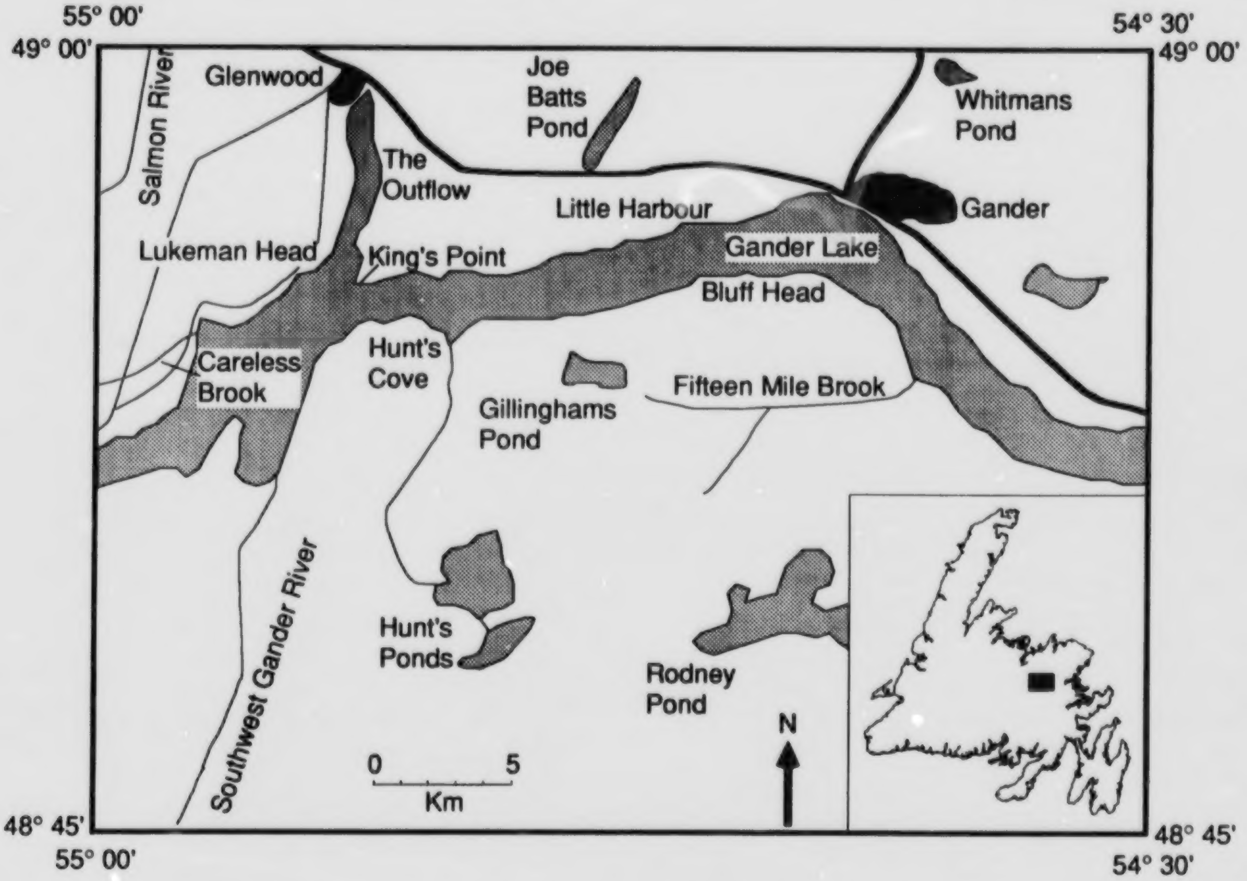
INTRODUCTION

Knowledge of the Quaternary geology of any area is crucial in the development of projects in the surficial environment. These could include siting of waste-disposal sites, groundwater studies, building and highway construction, municipal zoning for residential and commercial development, or in exploration for mineral or granular resources. The Gander map area (NTS 2D/15), as well as hosting several communities, has been the site of mineral exploration over the last 50 years or more. Although bedrock is well exposed over part of the area, much of it has a thick glacial sediment cover, which has impeded exploration. This is especially the case south of Gander Lake, where generally, bedrock exposure is limited to stream beds.

The objective of this project is to map the distribution of surficial sediments and features and describe their characteristics, map ice-flow directional indicators, and determine a glacial history for the area that will explain these observations. This will not only aid mineral-exploration activities by providing data on directions and possibly distances of transport of glacial sediment, but will also be a tool to be used by other projects influenced by surficial sediment.

LOCATION AND ACCESS

The Gander map area (NTS 2D/15) is located in central Newfoundland, between 48°45' and 49°00' north latitude, and 54°30' and 55°00' west longitude (Figure 1). It contains the communities of Gander and Glenwood, both north of Gander Lake, but is otherwise uninhabited apart from a few scattered cabins. Access to most of the field area was reasonable. The area north of Gander Lake is accessible by using the Trans-Canada Highway, and the road network around Gander. The southwest part of the area is accessible by all-terrain vehicles via a logging road south of Glenwood. The Rodney Pond area was reached by all-terrain vehicle via the Mint Brook road from Gambo. The shoreline of Gander Lake and some winter roads were accessible by boat. Other areas, especially north of Rodney Pond, and between Hunt's Ponds and Rodney Pond, were not examined because they are only efficiently accessed by helicopter.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Whitmans Pond
Salmon River
The Outflow
Little Harbour
Gander
Lukeman Head
King's Point
Gander Lake
Bluff Head
Careless Brook
Hunt's Cove
Gillinghams Pond
Fifteen Mile Brook
Southwest Gander River
Hunt's Ponds
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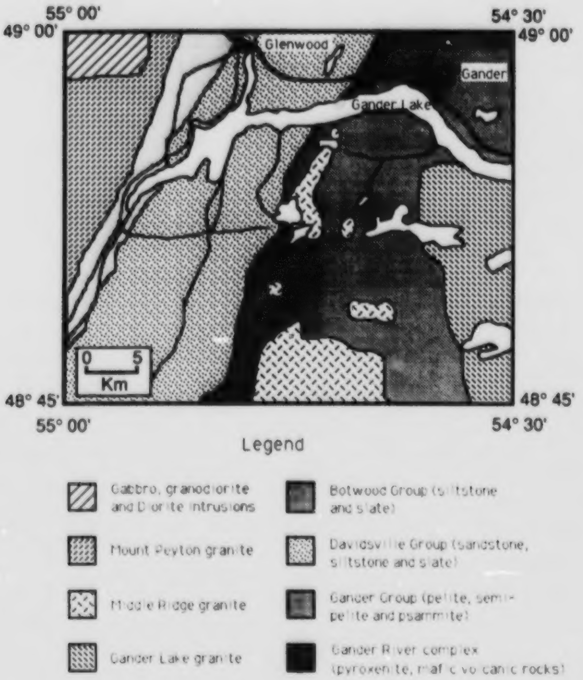
Figure 1. *Location map and places referred to in text.*

BEDROCK GEOLOGY

The study area straddles the boundary between the Gander and Dunnage tectonostratigraphic zones (Williams *et al.*, 1974; Figure 2). The Gander Zone constitutes the eastern part of the area and consists of a north-northeast-trending belt of Ordovician quartz-rich sandstones, siltstones, pelites, semipelites, psammites and volcanic rocks of the Gander Group (Blackwood, 1982). The Dunnage Zone to the west is composed of Middle Ordovician quartz-poor sandstone, shale, siltstone and conglomerate rocks of the Davidsville and Botwood groups, which are non-conformable over the Gander Group. The boundary between the two zones is faulted and has been previously known as the GRUB (Gander River Ultrabasic Belt), although the replacement term of Gander River complex has been proposed by O'Neill and Blackwood (1989). Rocks of the Gander River complex are composed mainly of pyroxenite, which has been locally serpentinized, but also include local exposures of carbonate, talc, and gabbro. These rocks are exposed over a width of 3 km north of Gander Lake, but only in restricted areas between Gander Lake and Hunt's Ponds to the south.

Both the Gander and Dunnage zones are intruded by a number of Devonian-age granitic plutons (Figure 2). The granitic plutons exposed in the area have distinctive characteristics. To the west, granite of the Mount Peyton intrusive suite is a fine- to medium-grained, equigranular, pink to red-weathering granite (Blackwood, 1982); gabbro intrusions are commonly associated with this unit. The Middle Ridge granite in the south is generally a medium- to coarse-grained, muscovite–biotite, white to pale-pink-weathering granite. A granite in the Gillinghams Pond area is similar in character, except that biotite rarely occurs (O'Neill, 1990). Small plutons of this unnamed granite occur to the west and northwest of Rodney Pond. The western part of the area is underlain by the Gander Lake granite, which contains potassium feldspar megacrysts in a biotite, quartz and feldspar matrix (O'Neill, 1990).

Historically, the main focus of mineral exploration in the area has been the ultramafic and associated rocks of the Gander River complex. Numerous asbestos, chromite and base-metal showings have been identified (Newfoundland Department of Mines and Energy, 1984), following initial work by the Newfoundland and Labrador Corporation Limited (NALCO) in the 1950's (Blackwood, 1982). More recently, exploration activity has centred on gold and stibnite occurrences within sediments of the Davidsville Group.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Legend
Gabbro, granodiorite and Diorite intrusions
Mount Peyton granite
Middle Ridge granite
Gander Lake granite
Botwood Group (siltstone and slate)
Davidsville Group (sandstone, siltstone and slate)
Gander Group (pelite, semi-pelite and psammite)
Gander River complex (pyroxenite, mafic volcanic rocks)

Figure 2. *Bedrock geology map of the Gander Lake area.*

O'Neill (1990) has postulated that the Gander Group sediments and the aureoles around the granitic intrusions may host precious metals.

PREVIOUS WORK

The Gander area straddles the 'inner' and 'outer drift zones' of Jenness (1960). The boundary between the two is marked by a discontinuous, boulder-till moraine, although it is obscured in the Gander area by heavy vegetation cover (Jenness, 1960). Jenness (1960) suggests that this zonation evolved as a result of rapid ice-retreat from its terminal positions on the northeast coast to a major stillstand position marked by the moraine. The outer drift zone is characterized by thin ground moraine of local origin and glaciofluvial sediments in valleys flowing out from the inner drift-zone area. Subsequent climatic amelioration led to final retreat of inland ice, much of which stagnated. The inner drift-zone area is characterized by thick, locally derived ground moraine, having a hummocky or ribbed surface topography. Jenness's (1960) description has largely been unchallenged since its publication. Lundqvist (1965) recorded several striations in the area, and Vanderveer and Taylor (1987), St. Croix and Taylor (1990) and Taylor and St. Croix (1989) described ice-flow patterns as showing an early eastward and a later north to northeastward flow.

FIELD PROGRAM

Bedrock outcrops were examined for striae or other ice-flow indicators and 113 striation sites were recorded. Detailed descriptions of surficial sediment were made from road, stream or lake exposures and included sedimentary structures, texture, and clast rock type. In areas with poor exposure, 15 pits were dug using a skidder-mounted backhoe, although these were largely confined to the northern part of the field area. In other areas of poor exposure, hand-dug testpits that penetrated to the soil C-horizon were examined. In 38 exposures of diamicton that extended into the C-horizon, clast fabrics of 25 elongate pebbles were measured. Results were plotted on a stereogram and analyzed using the Stereo™ software package for the Apple Macintosh-computer (MacEachran, 1990). Principal eigenvalues, which measure the strength of a fabric, and K values, which measure the modality of the fabric distribution, were produced using the methods outlined by Woodcock (1977). Normalized eigenvalues (S1) can range between 0.33 (random) and 1.0 (unidirectional). K values of less than 1 suggest girdle distributions. Matrix samples were taken from 103 sites for textural and geochemical analysis. Matrix samples (< 2 mm/-1ϕ) were sieved through a nest of 6 stainless-steel sieves (4ϕ to -1ϕ), and the silt/clay fraction ($< 4\ \phi$) was analyzed for grain-size distribution using a Coulter Counter, Model TAII-L (100 and 200 μm apertures). One-hundred and two samples of between 50 and 100 clasts each were also taken and rock types identified.

ICE FLOW

The glacial erosional evidence (mostly striae) suggests at least two major ice flows affected the area (Figure 3). The first was generally eastward (100 ± 20°) and is found across the whole area. In sites where two flows are encountered, the east flow is always preserved in the lee of, or crosscut by, a later ice flow that is generally north-northeastward (020 ± 20°). The poor striation preservation potential on the metasediments that surround the Gander Lake shore means little striae data was derived from this area. The early flow parallels the lake in its central part and some valley-parallel striae are found in the southeast oriented part of the lake. Ice-contact gravels and esker ridges identified in the Butts Pond area (Vanderveer *et al.*, 1987) at the eastern end of the lake suggest ice flowed through this area and into the sea.

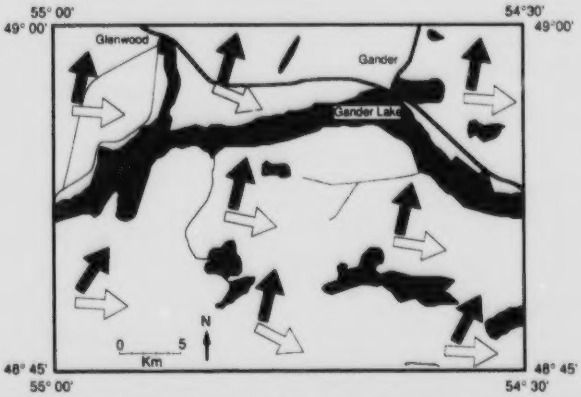
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Figure 3. *Simplified ice-flow direction map. The open arrows refer to the oldest recorded phase of movement; the black arrows refer to the most recent flow.*

The later flow roughly parallels the Southwest Gander River valley and The Outflow in the west, but obliquely crosses Gander Lake in the east.

Similar ice-flow directions to those described above have been reported from the southwest of the study area on the Northwest Gander River map area (NTS 2D/11) by Proudfoot *et al.* (1988), and by St. Croix and Taylor (1990) to the west. A postulated southward flow across the Gander Lake area from a source in the Long Range Mountains (see St. Croix and Taylor, 1990), which was based on southeastward-directed striae on the north coast, was only substantiated at one site, to the north of Gander Lake. Well-oriented clast fabrics (i.e., S1 ≤ 0.7 and K ≥ 1.0) that may be indicative of ice-flow directions (Harrison, 1957; Lawson, 1981; Dowdeswell and Sharp, 1986; Woodcock, 1977) are generally consistent with the erosional data. Most have a roughly north–south orientation (350 ± 30°), although several show trends perpendicular to last ice flow (see Batterson *et al.*, 1991 for more detail). These may either represent preservation of the earlier ice-flow event or transverse fabrics from the later flow.

CLAST PROVENANCE

It was anticipated that the diverse bedrock geology of the Gander area would make clast-provenance studies an effective method of determining paleo ice-flow directions, and distances of glacial transport. This method has been effective in other glaciated areas (e.g., Batterson, 1989), but its applicability is constrained by a number of factors including the physical characteristics of the rock type, which affect transport potential, correct rock-type identification and accurate bedrock mapping.

The resistance to comminution of a rock type during glacial transport is dependent on its hardness, grain size, and structure (e.g., a hard, massive granite clast will be transported farther than a well-bedded shale clast, which will be comminuted to finer grain sizes over a shorter distance) (Shilts, 1982). A small clast may not be representative of the rock type from which it has been derived, resulting in the mis-classification of a rock type (e.g., a diabase may be confused with a gabbro if fine grained enough, and individual components of a coarse-grained conglomerate may not be recognized as such). Similarly, structural features such as foliation may not be recognizable from clast fractions. Thus, it may be difficult to relate clasts to specific bedrock units.

In the Gander area, granites from three plutonic units are distinguished on the basis of colour, texture and mineralogy (Blackwood, 1982; O'Neill, 1990). Similarly, ultrabasic and associated volcanic rocks of the Gander River complex are restricted to a thin north-northeast- to south-southwest-trending belt through the central part of the area. Conglomerates are widely distributed throughout the Davidsville Group to the west, but have not been identified in the Gander Group within the field area or along expected ice-flow lines. These three groups of rocks were, therefore, considered useful indicators of glacial transport directions and distances.

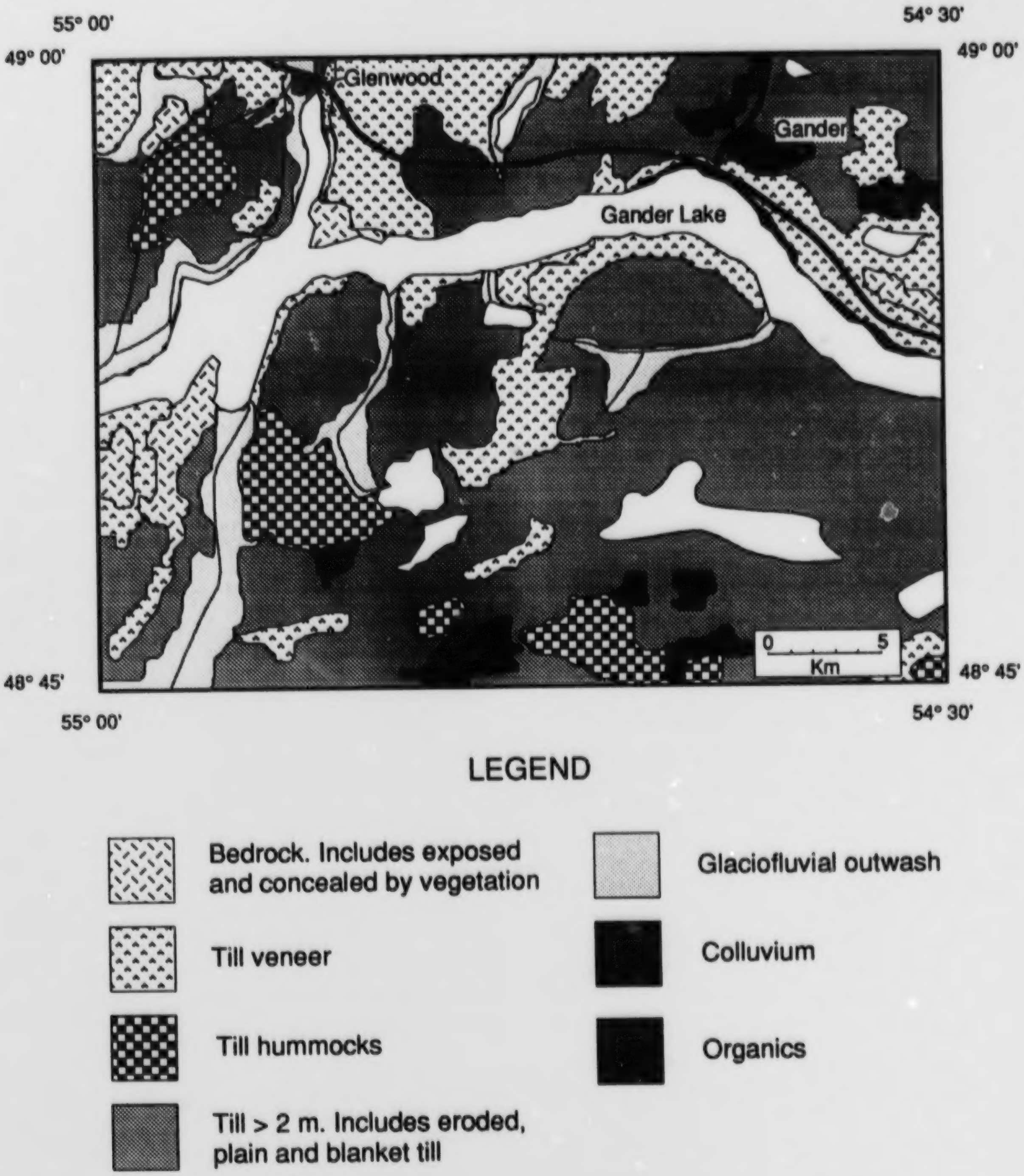
Diamictons contain clasts that are primarily derived from the underlying bedrock. Exceptions are conglomerate clasts of the Davidsville Group found at a site 3 km west of Gander, underlain by Gander Group rocks. Clasts of the Gander River complex were also identified in the Whitmans Pond area, and to the northwest and southwest of, as well as in, Gander. Granites from the Mount Peyton intrusive suite are widely dispersed across the area. In samples from the area of The Outflow, 15 km east of the nearest outcrop, Mount Peyton granites account for up to 20 percent of clasts. They are also common in the interfluve between the Northwest and Southwest Gander rivers to the south of Gander Lake. In glaciofluvial sediments in the Careless Brook and Salmon River areas, Mount Peyton granites form up to 90 percent of clasts. These granites were found as far east as Gander, 28 km from the nearest source. Murray (1882) also notes the eastward transport of Mount Peyton granites and identifies them at the eastern outlet of Gander Lake. Muscovite-rich granites from the Middle Ridge and Gillinghams Pond areas are common south of Gander Lake, and were identified at several locations to the north of the lake, but consistent with transport directions described earlier. South of Rodney Pond, a cluster of 6 sites, 4 km south of the pond show up to 40 percent granite clasts, with the nearest granite source mapped 5 km to the south. The clasts are pink, fine- to medium-grained granites and not the medium to coarse leucogranites mapped to the south. Although these clasts could represent transport in excess of 5 km, their concentration suggests that it is more likely that they have a more local source from a previously unmapped granite intrusion. O'Neill (personal communication, 1990) located one previously unrecognized granite outcrop on the southern margin of the map sheet, which may be part of this suggested intrusion. Along the logging road south of Rodney Pond, granite clasts in diamicton are fine to medium grained, in contrast to the published megacrystic leucogranite description (O'Neill, 1990). The area is heavily drift covered and the bedrock was mapped on the basis of few outcrops. It is likely, therefore, that finer grained phases of the Gander Lake granite exist, and these form the source for the clasts identified in the Rodney Pond area.

In summary, diamictons in the area are largely composed of locally derived material. However, they contain a component of far-travelled sediment. Mount Peyton granites have been identified 25 km east of the nearest source and granites from the Middle Ridge–Gillinghams Pond area have been found at least 18 km north of their nearest source. These distributions are consistent with the ice-flow history derived from striae, and suggest that sediment deposited during the early eastward flow event has been reworked by later, northward-flowing ice.

PHYSIOGRAPHY AND GEOMORPHOLOGY

The Gander map area can be divided into four geomorphological zones:

1) North of the Gander Lake basin, the contact between the Gander River complex and Gander Group is marked by increasing elevations, from 150 m a.s.l.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Glenwood
Gander
Gander Lake
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Km
48° 45'
48° 45'
55° 00'
54° 30'
LEGEND
Bedrock. Includes exposed and concealed by vegetation
Till veneer
Till hummocks
Till > 2 m. Includes eroded, plain and blanket till
Glaciofluvial outwash
Colluvium
Organics

Figure 4. *Simplified surficial geology map.*

in the east to less than 110 m a.s.l. in the west. Topography underlain by Gander Group rocks is flat and featureless, compared to the irregular topography to the west. Surficial sediment is generally thin (Figure 4), having numerous bedrock exposures, especially along the Trans-Canada Highway. An exception is an area of till ridges oriented transverse to flow that occur in the Whitmans Pond area, north of Gander (Figure 1).

2) South of the Gander Lake basin, the area is dominated by hilly topography, with elevations up to 250 m a.s.l. Hillsides are commonly incised by small meltwater channels 5 to 10 m wide and 2 to 3 m deep. Streams drain the lowlands between hills, the larger streams being Hunts Brook and Fifteen Mile Brook. Surficial sediments are thicker and have rare bedrock outcrops. Till hummocks are common, especially in the bog-covered lowlands south of Rodney Pond and around Hunt's Ponds (Plate 1).

Plate 1. *Coarse grained muscovite leucogranite boulders exposed on hummocks north of Gillinghams Pond. The underlying bedrock is Gander Group sediments. A thin surface cover of boulders is common across the study area and probably represents a supraglacial sediment.*

3) The west of the study area is dominated by glaciofluvial and alluvial sediments. The Southwest Gander River valley is about 6 km wide in the map area, with a flat, up to 1.5-km-wide, valley floor. The valley contains eroded and terraced outwash up to an elevation of about 98 m a.s.l., or 60 m above present river levels. Some sediment has been reworked by the present channel into an alluvial plain up to 1 km wide. Extensive outwash sediments occur in the Careless Brook valley, where terraces up to 40 m high were observed. Meltwater outflow from the Southwest Gander and Careless Brook valleys and from the Northwest Gander River valley (southwest of map area) apparently flowed northward through The Outflow into the modern Gander River valley. A veneer of outwash sands and gravels overlying diamicton is common in this area and beach sediments up to 39 m above Gander Lake have been identified. Outwash sediments also fill the Hunt's Brook valley coming out of Hunt's Ponds and entering Gander Lake at Hunt's Cove.

4) The dominant feature on the Gander map area is Gander Lake. The lake is 47 km long, an average of 1.9 km wide, has a surface area of 11,500 ha (Yoxall, 1981), and a surface elevation of 25 m a.s.l. Although the bathymetry of the lake is unknown, Jenness (1960) reports soundings in the Fifteen Mile Brook area at a maximum of 274 m, or 249 m below present sea level. Murray (1882) reports sounding depths of 123 m off King's Point, decreasing to 93 m in the Northwest Brook Cove and 27 m at the extreme eastern end of the lake. Jenness (1960) suggests that the lake is a fiord of glacial origin, being aligned with known paleo ice-flow directions, with an outlet to the sea through a presently outwash-filled valley to the east. To the south of the lake, hills rise to about 213 m a.s.l., giving a maximum relief of at least 487 m for the trough. The Gander Lake basin contains little evidence of glaciofluvial or fluvial activity to the east of King's Point. The lake shore is dominated by bedrock, and valley sides are mostly composed of a till veneer or bedrock having a thin vegetation cover. Exceptions are thicker colluvial sediment on the north shore of the lake in the Gander area and extensive areas of glacial sediment found to the east of Fifteen Mile Brook. The hillside in this area is composed of diamicton, dissected by numerous closely spaced meltwater channels. Two small eskers were also identified on the aerial photographs in this area.

QUATERNARY SEDIMENTS

Sedimentological analysis centred on diamictons because these are the sediments most used in mineral-exploration studies in drift-covered areas. Detailed descriptions are made from north of Gander Lake; south of the lake, where thicker drift is found, there were very few natural exposures and the use of the backhoe was limited due to time constraints. In this area, only inferences about sediment characteristics can be made. Other major sediment types in the area are also described.

DIAMICTONS

The major sediment type in the area is a reddish-brown to grey, sandy diamicton. Reddish-brown diamictons are generally confined to the west of the area, the colour likely being derived from the red sediments of the Botwood Group (Blackwood, 1982). In the areas underlain by Gander Group sediments, diamictons are generally grey. Diamictons throughout the map area have a similar sand-dominated matrix (Figure 5). The lack of variation is likely due to the consistency of bedrock, which forms the bulk of the matrix. Field estimates of the clast content of diamictons vary between 30 and 75 percent, having an average of about 50 percent. Clast to clast contacts are common in the coarser grained diamictons. Occasionally, fragile clasts (e.g., well-bedded, soft, shale) were found within the diamicton. Although grain-size distributions have not been completed on these samples, diamictons in the area appear to be poorly sorted.

Diamictons are commonly slightly to highly compacted, the degree of compaction being increasingly proportional to the fines content. Clasts are pebble to cobble sized, with boulders accounting for less than 10 percent of clasts by

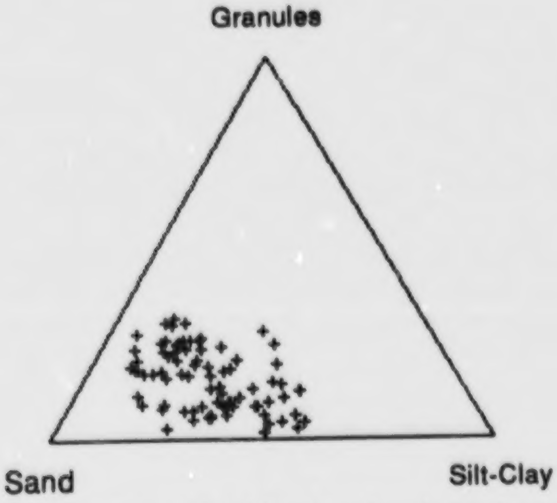

Figure 5. *Ternary plot of diamictons from the Gander map sheet area.*

volume. Generally, clasts are sub-angular to sub-rounded, the degree of roundness mainly being related to the rock type. Granite clasts are commonly sub-rounded because of their hardness and texture. Metasediments are generally sub-angular. Similarly, preservation of abrasion features on clasts is related to rock type. Fine-grained, hard, rock types (e.g., siltstones, rhyolites) are commonly striated in diamictons in the Gander area. Coarser grained, softer rock types (e.g., metasediments) rarely preserve striations. The upper surface of clasts commonly have a thin (< 0.2 mm) silt to fine sand coating that is difficult to remove by washing. Clast fabrics are variable. Strong fabrics (i.e., those with an S1 > 0.6 and K > 1.0) show clast orientations generally consistent with the last phase of ice movement (Batterson *et al.*, 1990).

In small exposures, or where moist, the diamictons appear massive. However, in larger exposures, particularly those which have been exposed for some time, sedimentary structures were found. Beneath cobbles and boulders, a thin (2 to 5 grains thick) layer of sand or granule gravel is common, and rarely, oval lenses of moderately sorted sand and granule gravel were noted. Sub-horizontal to horizontal fissility is common.

The characteristics of diamictons outlined above are generally consistent with a subglacial melt-out till origin (Dowdeswell and Sharp, 1986; Dreimanis, 1988; Lawson, 1981; Shaw, 1982). The striated clasts, their sub-rounded form and well-oriented clast fabrics is indicative of basal transport. The presence of sorted layers beneath clasts and throughout diamicton units suggests the presence of water during deposition, and the presence of fragile clasts indicates a passive depositional process. In melt-out tills, the clast fabric is inherited from the glacial transport process (Dreimanis, 1988) and is, therefore, commonly parallel to ice movement. However, Lawson (1981) notes the susceptibility of melt-out tills to resedimentation during and following deposition, which weakens clast fabrics. This could explain the variability of clast fabric noted in diamictons in this area that otherwise appear similar.

Complex stratigraphy in diamicton units is rarely exposed in the Gander area. In the Little Harbour area, west of Gander, 2 gravel pits reveal a complex stratigraphy. In the westernmost pit, located about 2 km northwest of Little Harbour, there is a 5 m exposure comprising 4 sediment units (Figure 6). The lowest unit (Unit 1) is a 2.5- to 3.0-m-thick, brownish, diamicton. It has a fine to medium sand matrix, with less than 10 percent silt-clay content. Clasts form about 60 percent of the unit are mostly pebble to boulder, angular to sub-angular, and of local provenance. Fine-grained clasts are commonly striated. Two clast fabrics were taken and provide well-oriented but girdle distributions (S1=0.72, K=0.58; S1=0.62, K=0.44). The diamicton is poorly compacted and contains numerous sub-horizontal, irregularly shaped lenses of massive coarse sand and granule gravel. Lenses are common beneath clasts.

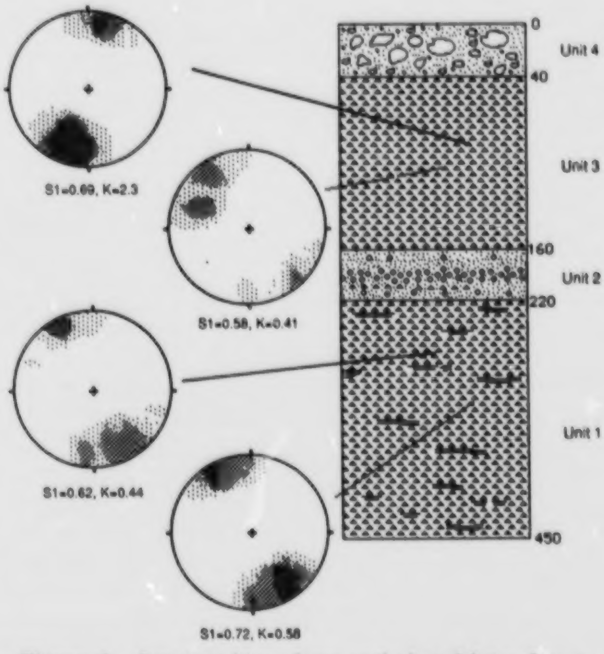

Figure 6. *Stratigraphic column and clast fabrics from a gravel pit in the Little Harbour area. Not drawn to scale. Refer to text for description of units.*

Overlying a sharp, undulating contact, Unit 2 is about 80 to 100 cm thick and is composed of interbedded sand, pebbly-sand, coarse sand, granule gravel and diamicton. Individual beds are thin (~5 cm), well to poorly sorted, normally graded, and contain irregularly shaped sand lenses. Sand layers are commonly deformed beneath clasts.

Above a sharp, undulating contact is a 90- to 120-cm-thick, reddish-brown diamicton (Unit 3). The matrix is fine sand to silt, with a 22 percent silt-clay content, and is moderately compact. Clasts are generally angular to sub-angular, and mostly of local provenance, including sediments, metasediments, and tuffs (Gander River complex). Fine-grained, pink, granites probably derived from the Mount Peyton intrusive suite are also found. Striated clasts are common. The clast content is about 50 percent, and clasts are granule gravel to boulder sized. Two clast fabrics were taken from this unit with a 5-m lateral displacement. They showed a strong fabric (SI=0.69, K=2.3), oriented 197 to 017°, parallel to local striae, and a moderately strong fabric with a girdle distribution (SI=0.58, K=0.41), oriented 134 to 314°. Concentrations of vertical clasts were noted within this unit.

The surface sediment (Unit 4) is a 50- to 80-cm-thick, coarse-grained, clast-rich diamicton. The unit is poorly compacted with 60 to 80 percent angular to sub-angular clasts having common leucogranites, similar to those exposed around Gillinghams Pond. Clasts from the Mount Peyton intrusive suite, which are common in the lower sediment, are absent. Striations were absent on clasts. The matrix is fine sand, having less than 10 percent silt and clay.

This exposure contains 3 diamicton units and a subglacial fluvial deposit. Unit 1 is probably a subglacial meltout till (Figure 6). The moderately oriented clast fabrics, sub-rounded, striated clasts and numerous lenses, especially beneath clasts, are consistent with this interpretation (Dreimanis, 1988; Shaw, 1982). Similarly, moderately strong but girdle clast fabrics may reflect reduction of inclination of clasts as a result of melting ice during deposition (Dreimanis, 1988). The low compaction is likely a function of the sandy matrix. The texture, structure and vertical and lateral variability of the underlying sand and gravel unit are consistent with deposition in a fluvial environment. The deformation of sand beds by clasts, the interbeds of diamicton and the overlying diamicton having sharp basal contacts, suggest deposition at the base of a glacier. Subglacial drainage may occur as sheet flow, through microchannels within diamicton (forming sorted sand and granule gravel lenses), or as larger channels cut into the ice or bedrock. Sediments within these channels are similar to their proglacial counterparts (Drewry, 1986). The undulating contact with the underlying diamicton and the deformation of sand beds beneath clasts suggest these sediments were deposited englacially within a channel cut into the ice ('Rothlisberger channel'; Rothlisberger, 1972), and draped over the underlying diamicton. Unit 3 is probably a subglacial melt-out till. The reddish-brown matrix and moderate compaction is similar to diamictons described in the west part of the area. It differs from the lowest diamicton in colour, grain size, compaction and clast provenance. The first three differences reflect the finer sediment matrix, and the clast provenance suggests a local origin. The fabrics, clast shape and striated clasts are all consistent with a subglacial melt-out origin. The surface diamicton is a supraglacial melt-out till. The coarse matrix, angular to sub-angular non-striated clasts, low compaction, and stratigraphic position are consistent with this interpretation (Eyles, 1979; Dreimanis, 1988). The presence of clasts derived from the Gillinghams Pond area suggests transportation northward, consistent with regional striae.

A similar stratigraphy is recorded in a pit about 2 km southeast. It exposes the three diamicton units described above, but does not have the intervening sand and gravel unit. The absence of this unit at this site is perhaps further evidence for the sediments' origin within a subglacial channel.

GLACIOFLUVIAL AND GLACIOLACUSTRINE SEDIMENTS

Glaciofluvial sediments are common in valleys across the area (Figure 4). The areally largest deposits are within the Southwest Gander River valley, and within the area of The Outflow into modern Gander River. Thick exposures of sediment are rare, but where found, they have a similar stratigraphy. Two terrace scarps within the Southwest Gander River valley, one 10 m and the other 20 m high and up to 50 m wide, show a basal unit of > 5 m thick of moderate to well-sorted, coarse to medium sand. This unit has interbeds of well-sorted, coarse or medium sand, and has planar tabular crossbedding, with the direction of flow consistent with modern drainage (northward). This unit coarsens upward into a 2- to 4-m- thick sandy pebble gravel. The gravel has a 50 to 80 percent clast content, having sub-rounded to rounded, pebble to cobble clasts, of mixed rock types. The matrix is medium to coarse sand, with a silt-clay content of about 10 percent (Figure 7). Discontinuous beds of moderately sorted sands or granule gravels are common, especially beneath clasts. The beds are irregularly shaped, although roughly horizontal, and are up to 5 cm diameter and 2 cm thick. In abandoned borrow pits in the Hunt's Ponds area, these beds were steeply dipping (40°). The B-soil horizon is commonly cemented (orthic). Sediment similar to the upper sandy gravel is commonly exposed in glaciofluvial terrain across the area, up to 60 m above current river levels. Well-sorted sands and gravels are relatively rare, and apart from the Southwest Gander River valley, were only found in the Careless Brook valley and in the Fifteen Mile Brook valley in an abandoned gravel pit.

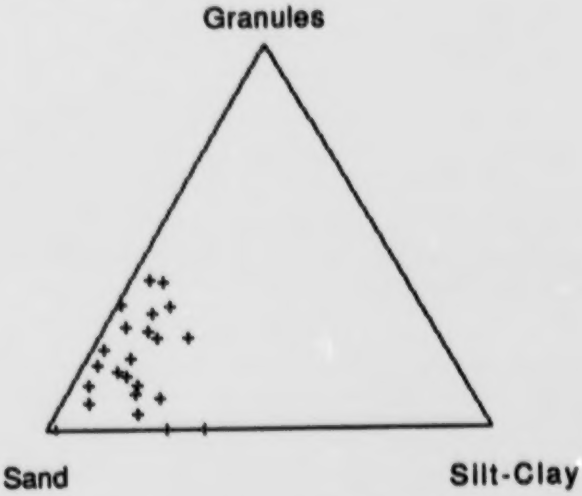

Figure 7. *Ternary plot of glaciofluvial sediments from the Gander map sheet area.*

Poorly sorted sands and gravels are consistent with deposition within glacial meltwater streams, which characteristically have rapid changes in discharge (Sugden and John, 1979). Similarly, steeply dipping beds of the type found at Hunt's Ponds are consistent with deposition in an ice-contact environment (Sugden and John, 1979). However, the presence of thick, well-sorted, crossbedded sands is puzzling, because they are atypical of glaciofluvial outwash environments. It is possible that these sediments reflect deposition within a sandy fluvial system (Walker and Cant, 1984), or deposition within a delta (Miall, 1984).

In the area of The Outflow, glaciofluvial sediments commonly overlie diamictons, up to an elevation of about 60 m a.s.l., or 35 m above the present river level. Glaciofluvial deposits at this elevation were not found elsewhere around the margins of Gander Lake. At Hunts Cove, an outwash terrace associated with flow out of Hunts Brook is 5 m above the present lake level, a similar elevation to deposits at the mouth of Fifteen Mile Brook. Much of the area between modern valleys along the lake exposes either diamictons or colluvium. Boulders along the lake shore are angular and of local provenance. This contrasts with The Outflow area where boulders are commonly rounded and of mixed rock types. This evidence suggests that water levels were higher in the area of The Outflow than elsewhere on Gander Lake.

Further evidence for higher water levels in Gander Lake was found in a backhoe-dug pit near Lukeman Head at an elevation of about 64 m a.s.l. (Figure 8; Plate 2). The stratigraphy showed a basal greenish-grey diamicton unit overlain by a unit composed of interbedded 5- to 15-cm-thick draped silt-clay laminae (Gustavson *et al.*, 1975), and up to 25-cm-thick massive fine sands, capped by a 3-cm-thick massive clay bed. The silt-clay laminae commonly show rhythmic alternation between clay and silt. Clasts are rare, and deform underlying laminae. The contacts between these interbeds are commonly rippled, with a 5 to 20 cm wavelength and a 0.3 to 1.2 cm amplitude. Overlying a sharp contact is a 40-cm-thick, rippled, reverse graded, fine to coarse sand unit. Ripples are sharp crested with a 10 cm wavelength and 2 cm amplitude. The ripples are defined by clay drapes on their upper surfaces. Overlying another sharp contact is a 2.4-m-thick unit of poorly sorted granule gravel, interbedded with well-sorted, planar-bedded granule to pebble gravels. These gravels are well rounded, clast supported, open-work gravels dipping gently southeastward.

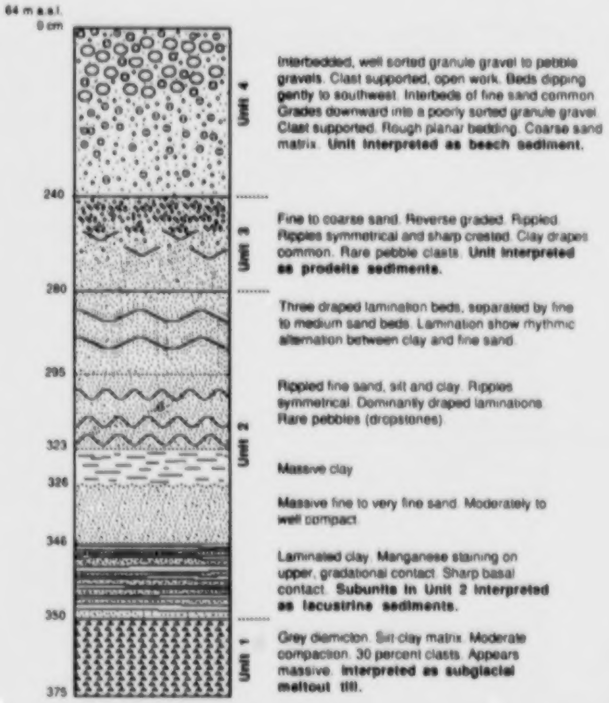
64 m a.s.l.
0 cm
240
280
295
323
326
346
350
375
Unit 4
Unit 3
Unit 2
Unit 1
Interbedded, well sorted granule gravel to pebble gravels. Clast supported, open work. Beds dipping gently to southwest. Interbeds of fine sand common. Grades downward into a poorly sorted granule gravel. Clast supported. Rough planar bedding. Coarse sand matrix. Unit interpreted as beach sediment.
Fine to coarse sand. Reverse graded. Rippled. Ripples symmetrical and sharp crested. Clay drapes common. Rare pebble clasts. Unit interpreted as prodelta sediments.
Three draped lamination beds, separated by fine to medium sand beds. Lamination show rhythmic alternation between clay and fine sand.
Rippled fine sand, silt and clay. Ripples symmetrical. Dominantly draped laminations. Rare pebbles (dropstones).
Massive clay
Massive fine to very fine sand. Moderately to well compact.
Laminated clay. Manganese staining on upper, gradational contact. Sharp basal contact. Subunits in Unit 2 interpreted as lacustrine sediments.
Grey diamicton. Silt-clay matrix. Moderate compaction. 30 percent clasts. Appears massive. Interpreted as subglacial meltout till.

Figure 8. *Stratigraphic column of a backhoe-exposed section in the Lukeman Head area. Not drawn to scale. Refer to text for unit descriptions and to Plate 2 for photograph of section.*

This stratigraphy is interpreted as representing four depositional environments. The lower diamicton appears similar to those described earlier and is tentatively assigned a subglacial origin. The overlying unit is interpreted as a lacustrine or glaciolacustrine sediment. The laminated silt-clay, draped laminations, lack of gravel beds and deformation of laminae by clasts that represent dropstones, are consistent with deposition by suspension settling (Ashley, 1988; Gustavson *et al.*, 1975). The rippled sands and draped laminations having rare dropstones overlying the lacustrine sediments suggest deposition by intermittent current flow and suspension settling (Ashley, 1988), probably closer to a sediment inflow area (e.g., a delta) than Unit 2. The overlying coarse, planar-bedded, open-work gravels of the surface unit are interpreted as regressive and transgressive beach deposits (Postma and Nemec, 1990). These beach deposits mark the upper limit of lacustrine activity in the area. The level of beach sediments is similar to the elevation of well-sorted sands described from the Southwest Gander River valley. Therefore, it is possible that these sediments may represent deltaic deposition.

COLLUVIAL SEDIMENTS

On the north shore of Gander Lake, particularly in the vicinity of Gander and on the south shore in the area of Bluff Head, sediments interpreted as colluvium were found. Both these areas lie at the base of steep slopes (Figure 4). Sediment forms 3 to 4 m bluffs in these areas and is composed of a clast-rich diamicton. Matrix is fine sand, having a silt-clay content of 10 to 15 percent, and forms 30 percent or less of the sediment. Clasts are pebble to cobble size, sub-angular to angular, and almost entirely of local origin. The unit is commonly clast supported, with clasts apparently dipping parallel to the slope. On the shore of Gander Lake, about 2 km southeast of Gander at the pumping station, colluvial sediments have incorporated at least 2 organic-rich horizons.

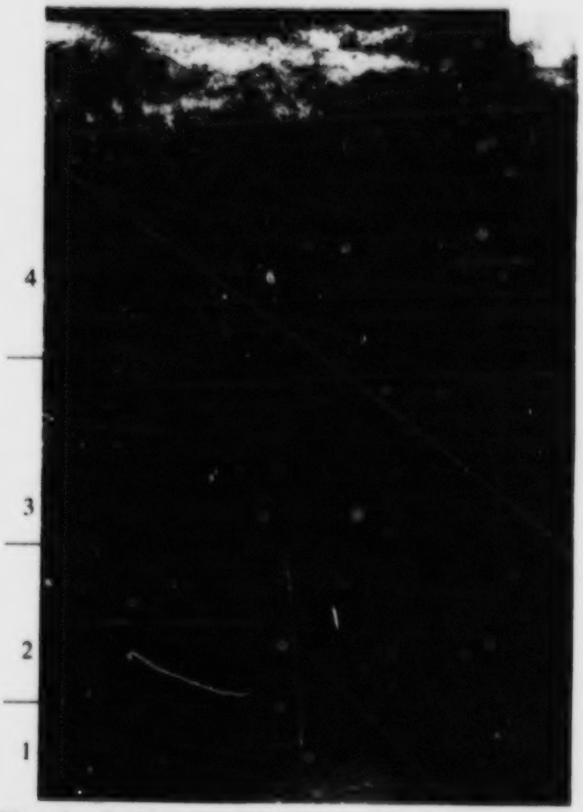

Plate 2. *Backhoe-exposed section in the Lukeman Head area. Trowel for scale. Refer to Figure 8 and the text for details.*

GLACIAL HISTORY–PRELIMINARY OBSERVATIONS

The glacial history of the Gander area is, as yet, poorly understood. The area has been affected by at least two glacial-flow events. The first was from a source to the west, and is consistent with regional ice-flow patterns described by St. Croix and Taylor (1990, this volume). This flow event transported sediment up to 25 km, although most material was probably transported less than 2 km. This eastward-moving ice flow was parallel to Gander Lake, at least in its western part, and suggests that the lake has been modified or formed by glacial action. The depth of the lake, the sediment-filled eastern outlet valley that leads to Freshwater Bay, and its orientation with regards to paleo ice-flow directions led Murray (1882) and Jenness (1960) to speculate that the lake is a fjord. It can be further speculated that Gander Lake was open to the sea at the onset of the last glacial period. No marine sediments were found to support this suggestion, although it is likely that these would lie below the current water level of the lake. The most recent flow direction, as shown by striae, clast provenance and fabrics, was generally north-northeastward, transverse to the lake. It is likely the Gander Lake valley was ice filled at this time.

As deglaciation proceeded, ice retreated toward the higher land to the south of the lake. Many of the glacial meltwater channels in this area were probably cut at this time. The valleys of the Northwest and Southwest Gander rivers acted as major conduits of meltwater drainage, containing streams that deposited sediments up to 60 m above the current river levels. Smaller valleys such as Careless Brook, Joe Batts Brook, and Salmon River also carried glacial meltwater. In the area of The Outflow, higher water levels are shown by waterlain sediments near Lukeman Head, and the possible existence of deltaic deposits in the Southwest Gander River valley. The lack of these deposits to the east of Kings Point suggests that higher water levels did not extend to this area, possibly because the lake was ice filled at this time. However, it is also possible that higher water levels were the result of marine incursion. Raised marine features on the coast have not been examined in detail, but Grant (1980) reports Late Wisconsinan marine limits near Musgrave Harbour on the north coast at 43 m a.s.l. Marine limit at the coast at the eastern end of the lake has been reported at about 30 m a.s.l. (Jenness, 1960; Grant, 1980), although it is difficult to explain the presence of ice-contact sands and gravels, and eskers in the outlet valley at the eastern end of the lake if filled by marine water. Higher water levels drained through the modern Gander River valley. Remnant ice in Gander Lake stagnated, as did ice to the south of the lake. The Hunt's Brook and Fifteen Mile Brook valleys were meltwater conduits at this time.

During the Holocene, organic deposits developed in the poorer drained areas, and colluvial deposits formed at the base of the steeper slopes. Both these processes continue today, although vegetated slopes have retarded the rate of colluviation.

IMPLICATIONS FOR MINERAL EXPLORATION

Despite common erratics identified as originating from the Mount Peyton area to the west, transported by eastward-flowing ice, evidence from striations and from clast fabrics suggests that the last sediment-moving ice-flow event was north to north-northeastward. Most diamictons in the area have been interpreted as basal melt-out tills. The sediment comprising basal melt-out tills are, in general, farther transported than a lodgement till (Dreimanis, 1988), but the clasts suggest that it is representative of the local bedrock, and is, therefore, a suitable sampling medium. However, surface clast-rich diamictons should be avoided. These have been interpreted as supraglacial sediments, which are largely composed of far-travelled sediment. Glaciofluvial sediments should be avoided in any routine sampling program, as the sediment is derived through a fluvial transport system that may carry material long distances from its source. Colluvial sediments should not be sampled in association with diamicton samples, because of the differing transport histories. Colluvium is derived through slope processes, and therefore, samples will be reflective of the up-slope, rather than up-ice direction.

Overall, the glacial history of the Gander area is complex. Mineral-exploration activity in drift-covered areas should identify the genetic environment of samples to examine their suitability to drift-exploration programs. Failure to do so may result in erroneous conclusions regarding the potential source of geochemical or float anomalies in the surficial environment.

IMPLICATIONS FOR LAND-USE PLANNING

In the Gander area, the results of the surficial mapping suggest that the siting of waste-disposal sites (in any surficial sediment) within the drainage basin used for town water-supplies is not recommended. All surficial sediments have a sandy matrix, having numerous sorted lenses that would enhance percolation of pollutants into the groundwater system. The siting of waste-disposal sites on glaciofluvial sediment would also be potentially unsafe for similar reasons. The presence of colluvial deposits at the base of many steeper slopes suggests they are unstable, and therefore, should be avoided as sites for any construction activity. Surficial mapping also points to several new areas of aggregate-resource potential, in particular in the Fifteen Mile Brook area. The suitable zonation of these resources to allow their exploitation, along with those reported by Ricketts and McGrath (1990), are also important to the efficient development of this area.

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REFERENCES

Ashley, G.M.
1988: Classification of glaciolacustrine sediments. *In* Genetic Classification of Glacigenic Deposits. *Edited by* R.P. Goldthwait and C.L. Matsch. A.A. Balkema, Rotterdam, pages 243-260.

Batterson, M.J.
1989: Glacial dispersal from the Strange Lake alkalic complex, northern Labrador. *In* Drift Prospecting. *Edited by* R.N.W. DiLabio and W.B. Coker. Geological Survey of Canada, Paper 89-20, pages 31-40.

Batterson M.J., St. Croix, L., Taylor, D.M. and Vatcher, S.
1991: Ice-flow indicators on the Gander Lake map sheet (NTS 2D/15). Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File 2D/15 (233), Map number 91-01.

Blackwood, R.F.
1982: Geology of the Gander Lake (2D/15) and Gander River (2E/2) area. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-4, 56 pages.

Dowdeswell, J.A. and Sharp M.J.
1986: Characterization of pebble fabrics in modern terrestrial glacigenic sediments. Sedimentology, Volume 33, pages 699-710.

Drewry, D.
1986: Glacial Geologic Processes. Edward Arnold, London, 276 pages.

Dreimanis, A.
1988: Tills: their genetic terminology and classification. *In* Genetic Classification of Glacigenic Deposits. *Edited by* R.P. Goldthwait and C.L. Matsch. A.A. Balkema, Rotterdam, pages 17-86.

Eyles, N.
1979: Facies of supraglacial sedimentation on Icelandic and Alpine temperate glaciers. Canadian Journal of Earth Sciences, Volume 16, pages 1341-1361.

Grant, D.R.
1980: Quaternary sea-level change in Atlantic Canada as an indication of crustal delevelling. *In* Earth Rheology, Isostasy and Eustasy. *Edited by* N.A. Morner. Wiley, pages 201-214.

Gustavson, T.C., Ashley, G.A. and Boothroyd, J.C.
1975: Depositional sequences in glaciolacustrine deltas. *In* Glaciofluvial and Glaciolacustrine Sedimentation. *Edited by* A.V. Jopling and B.C. MacDonald. Tulsa, Oklahoma, S.E.P.M. Special Publication, Number 23, pages 264-280.

Harrison, P.
1957: A clay-till fabric, its character and origin. Journal of Geology, Volume 65, pages 275-308.

Jenness, S.E.
1960: Late Pleistocene glaciation of eastern Newfoundland. Bulletin of the Geological Society of America, Volume 71, pages 161-179.

Lawson, D.E.
1981: Distinguishing characteristics of diamictons at the margin of the Matanuska Glacier, Alaska. Annals of Glaciology, Volume 2, pages 78-84.

Lundqvist, J.
1965: Glacial geology in northeastern Newfoundland. Geologiska Foreningens i Stockholm Forhandlingar, Volume 87, pages 285-306.

MacEachran, D.B.
1990: Stereo™, the stereographic projection software program for the Apple Macintosh-computer. Distributed by Rockware Inc., Wheat Ridge, Colorado, U.S.A.

Miall, A.D.
1984: Deltas. *In* Facies Models, second edition. *Edited by* R.G. Walker. Geoscience Canada, Reprint series 1, pages 105-118.

Murray, A.
1882: Glaciation of Newfoundland. Proceedings and transactions of the Royal Society of Canada, Volume 1, pages 55-76.

Newfoundland Department of Mines and Energy.
1984: Mineral occurrence map, Gander Lake (2D), Map 8445.

O'Neill, P.P.
1990: Geology of the northeast Gander Lake map area (NTS 2D/15) and the northwest Gambo map area (NTS 2D/16). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 317-326.

O'Neill, P.P. and Blackwood, R.F.
1989: A proposal for revised stratigraphic nomenclature of the Gander and Davidsville groups and the Gander River ultrabasic belt, of northeastern Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 127-130.

Postma, G. and Nemec, W.
1990: Regressive and transgressive sequences in a raised Holocene gravelly beach, southwestern Crete. Sedimentology, Volume 37, pages 907-920.

Proudfoot, D.N., Scott, S., St. Croix, L., Taylor, D.M. and Vanderveer, D.G.
1988: Glacial striations in southeast-central Newfoundland. 1:250,000 scale. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 88-102, Open File (NFLD 1725).

Ricketts, M.J. and McGrath, J.
1990: Granular aggregate resource mapping of the Gander Lake (NTS 2D/15), Gander River (NTS 2E/2) and Comfort Cove–Newstead (NTS 2E/7) map areas. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 65-76.

Rothlisberger, H.
1972: Water pressure in intra- and subglacial channels. Journal of Glaciology, Volume 11, pages 177-203.

Shaw, J.
1982: Melt-out till in the Edmonton area, Alberta, Canada. Canadian Journal of Earth Sciences, Volume 19, pages 1548-1569.

Shilts, W.W.
1982: Glacial dispersal: principles and practical applications. Geoscience Canada, Volume 9, pages 42-48.

St. Croix, L. and Taylor, D.M.
1990: Ice flow in north-central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 85-88.

This volume: Regional striation survey and deglacial history of the Notre Dame Bay area, Newfoundland.

Sugden, D.E. and John, B.S.
1976: Glaciers and Landscape. Edward Arnold. London, 376 pages.

Taylor, D.M. and St. Croix, L.
1989: Glacial striations in north-central Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 89-108, Open File Nfld (1875).

Vanderveer, D.G. and Taylor, D.M.
1987: Quaternary mapping in the Gander River area, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 39-44.

Vanderveer, D.G., Taylor, D.M. and Batterson, M.J.
1987: Landform classification maps for the Gander area (NTS 2D/16, 2E/1, 2E/2). Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Nfld (1575).

Walker, R.G. and Cant, D.J.
1984: Sandy fluvial systems. *In* Facies Models, second edition. *Edited by* R.G. Walker. Geoscience Canada, Reprint series 1, pages 71-90.

Williams, H., Kennedy, M.J. and Neale, E.R.W.
1974: The northward termination of the Appalachian Orogen. *In* Ocean Basins and Margins. *Edited by* A.E.M. Nairn and F.G. Stehli. Volume 2, Plenum Press, New York, pages 79-123.

Woodcock, N.H.
1977: Specification of fabric shapes using the eigenvalue method. Bulletin of the Geological Society of America, Volume 88, pages 1231-1236.

Yoxall, W.H.
1981: The surface waters and associated landforms of the Island of Newfoundland. *In* The Natural Environment of Newfoundland: Past and Present. *Edited by* A.G. Macpherson and J.B. Macpherson. Department of Geography, Memorial University of Newfoundland, pages 154-188.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 13-18

BEDROCK AGGREGATE SURVEYS IN THE BULL ARM–MOSQUITO COVE AREAS, TRINITY BAY, AND CENTRAL NEWFOUNDLAND

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ABSTRACT

The 1990 field program consisted of two field surveys; a detailed investigation of the Bull Arm–Mosquito Cove areas, Trinity Bay and a reconnaissance survey in central Newfoundland. The first was an assessment survey, done to determine the quality and quantity of bedrock for use as aggregate in the construction of the concrete, gravity-based structures, and associated site infrastructure. Fifty-seven sites were examined in this region, and 52 samples collected. Based on preliminary physical property results, (hardness, freshness and rock type), 20 samples are considered to be of high quality, 18 samples are considered to be of marginal quality and 14 samples are considered to be of low quality.

The second survey was a reconnaissance investigation, which was done to determine the quality and quantity of bedrock aggregate for local industrial use in central Newfoundlnad. A total of 509 sites were examined and 270 samples collected. Based on preliminary physical property results (hardness, freshness and rock type), 122 samples are considered to be of high quality, 90 samples are considered to be of marginal quality and 58 samples are considered to be low quality.

Analyses of geotechnical properties of bedrock, including geological structures, presence of deleterious substances, petrographic analysis and number, abrasion, and soundness are presently under study, whereas alkali–reactivity tests have been performed on selected samples.

INTRODUCTION

The announcement in August 1990 that Mosquito Cove was to be the construction site of the offshore concrete gravity-based structure (GBS), initiated a detailed study for potential bedrock-aggregate sites in the Bull Arm–Mosquito Cove areas (Figure 1).

Granular material (sand and gravel) would be ideal for this project, however, it is not available on or near the proposed site (F.T. Kirby, personal communication, 1990), and therefore the bedrock-aggregate potential in the adjacent region was examined; this is the object of this report.

The second half of the field season was located in central Newfoundland (Grand Falls–Baie Verte Peninsula) (Figure 2). This was a reconnaissance investigation, which examined all the roadcuts, quarries and natural bedrock outcrops along highways and side roads, looking for sites of potential bedrock aggregate. The project is a continuation of a province-wide survey to identify potential high-quality bedrock and granular aggregate sites for local use (see Ricketts and McGrath, 1990).

GENERAL GEOLOGY

The geology of the Bull Arm–Mosquito Cove area consists of Cambrian volcanic and sedimentary rocks of the Musgravetown Group (King, 1988). The volcanic rocks consist of basalt, andesite, rhyolite and pyroclasts (mafic and felsic tuffs) of the Bull Arm Formation (King, 1988). The sedimentary rocks consist of sandstones, silstones and conglomerates of the Big Head, Maturin Point and Trinny Cove formations (King, 1988).

The general geology of central Newfoundland (Figure 2) consists of felsic to mafic volcanic rocks and minor occurrences of sedimentary rocks of the Robert's Arm, Springdale, Betts Cove, Buchans, Lush's Bight, Mic Mac Lake, Flatwater Pond, Goldson, Pacquet Harbour, Cape St. John and Snooks Arm groups and Lawrenceton, Sansom and New Bay formations (Kean *et al.*, 1981, Hibbard, 1983). Medium- to coarse-grained igneous rocks are characteristic of the Topsails, Dunamagon, Burlington, Cape Brule Porphyry, Halls Bay and Loon Bay intrusions and metamorphic rocks of the Birchy Complex, Rattling Brook, Old House and White Bay groups, the Garden Cove and Pigeon Island formations, the East Pond Metamorphic suite and the Dunnage Melange (Kean *et al.*, 1981; Hibbard, 1983).

FIELD WORK

Field work consisted of boat and foot-traverses along the shores of Bull Arm, Trinity Bay; and in central Newfoundland, mainly highway traverses along the Trans-Canada Highway and various side roads, including visits to all rock quarries in the area between Grand Falls and the Baie Verte Peninsula.

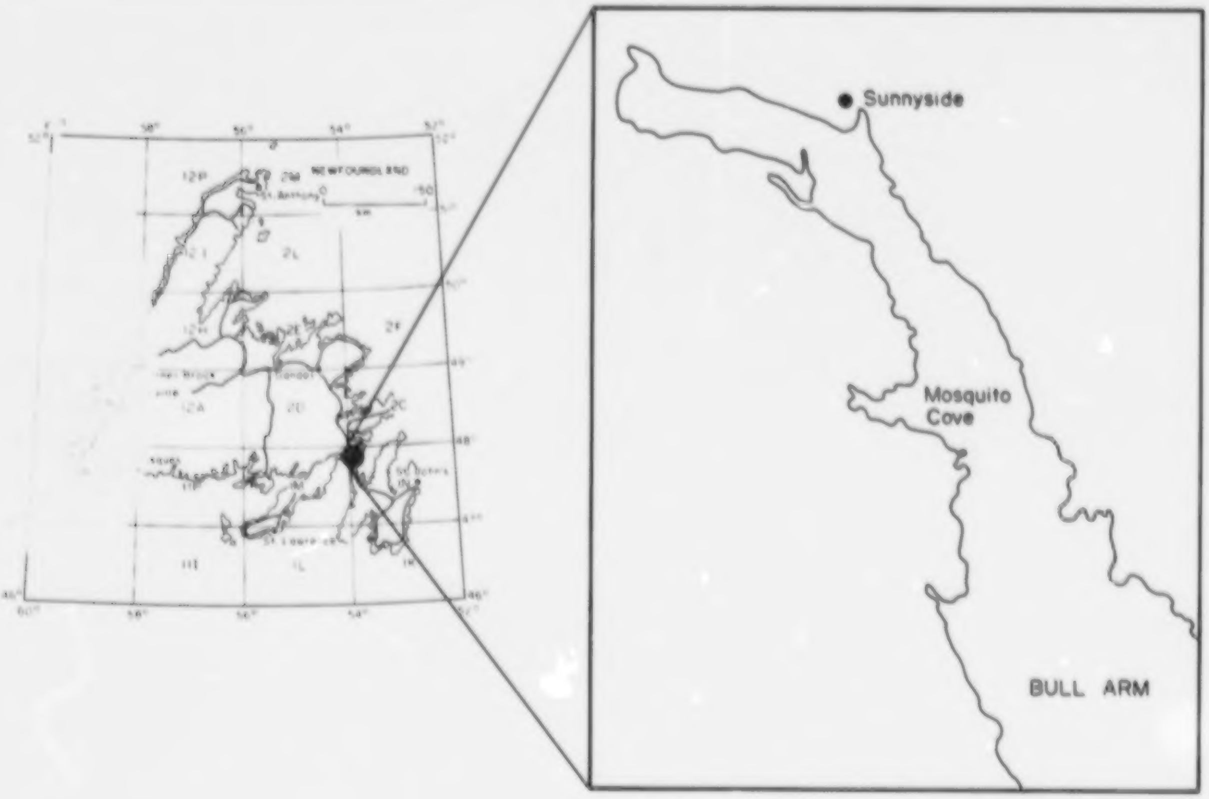
Sunnyside
Mosquito Cove
BULL ARM
NEWFOUNDLAND
St. Anthony
km
0
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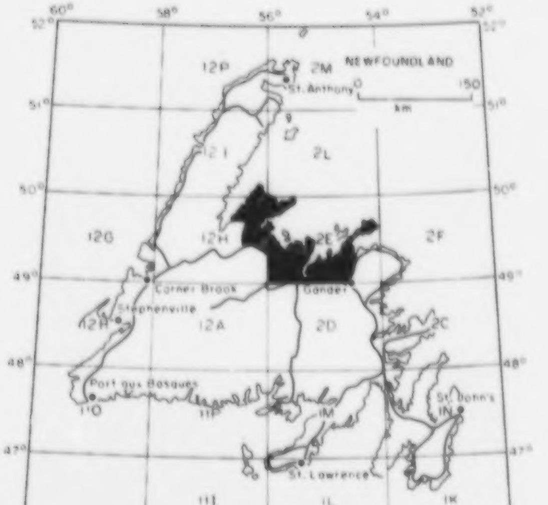
Figure 1. *Location map of study area in Bull Arm, Trinity Bay.*


60°
58°
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NEWFOUNDLAND
St. Anthony
km
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12P
2M
12I
2L
12G
12H
2E
2F
Corner Brook
Stephenville
12B
12A
Gander
2D
2C
Port aux Basques
11O
11P
1M
St. John's
1N
St. Lawrence
11I
1L
1K

Figure 2. *Location map of study area in central Newfoundland.*

Field investigations at each site may include rock identification, representative sampling, and the description of geological features. The site investigations methodology is reported in Bragg (1986, 1989) and Bragg and Norman (1988).

Once site investigations were completed, an initial quality reference (petrographic number) is given to each sample based on deleterious substances present and petrographic factors. Deleterious substances are materials that occur within or on the rock surface, and which are capable of producing adverse effects (e.g., chemical reactions with other minerals), resulting in a deterioration of the rock or cement binder when used in concrete or asphalt. Common deleterious substances include clay minerals, organic matter, mica, iron and manganese oxide staining, and cherty or fine-grained siliceous material. Alteration zones, encrustations and weathering are also factors that are considered to be deleterious to the quality of the rock aggregate (American Society for Testing and Materials (ASTM), 1985, 1986, 1987b; Bragg, 1989).

A petrographic number (P.N.) is calculated for each site and this is a preliminary measure of the quality of material for aggregate purposes. The petrographic number is calculated by sampling 100 clasts/fragments and assigning a petrographic factor to each clast/fragment. The petrographic factor (P.F.) ranges from 1 (best) to 10 (worst) depending on rock type, freshness, hardness and deleterious substances present (Canadian Standards Association (CSA), 1973; Table 1), and

Table 1. Rock type and petrographic factors

Rock type	Classification	Factor
Carbonates (hard)	good	1
Carbonates (sandy, hard)	good	1
Sandstone (hard)	good	1
Gneiss (hard)	good	1
Quartzite (coarse grained)	good	1
Greywacke–arkose	good	1
Volcanic (slightly weathered)	good	1
Granite–diorite	good	1
Trap	good	1
Magnetite	good	1
Pyrite (disseminated in trap)	good	1
Iron-bearing quartzite	good	1
Sedimentary conglomerate (hard)	good	1
Carbonates (slightly weathered)	fair	3
Carbonates (sandy, medium hard)	fair	3
Sandstone (medium hard)	fair	3
Crystalline carbonates (hard)	fair	3
Crystalline carbonates (slightly weathered)	fair	3
Gneiss (soft)	fair	3
Chert and cherty carbonates	fair	3
Granite (friable)	fair	3
Volcanic (soft)	fair	3
Pyrite (pure)	fair	3
Flints and jaspers	fair	3
Carbonates (soft, slightly shaly)	poor	6
Carbonates (soft, sandy)	poor	6
Carbonates (deeply weathered)	poor	6
Carbonates (shaly clay)	poor	6
Carbonates (ochreous)	poor	6
Chert and cherty carbonates (weathered)	poor	6
Sandstone (soft, friable)	poor	6
Quartzite (fine grained)	poor	6
Crystalline carbonates (very soft, porous)	poor	6
Gneiss (friable)	poor	6
Granite (friable)	poor	6
Encrustations	poor	6
Cementations	poor	6
Schist (soft)	poor	6
Ochre	deleterious	10
Shale	deleterious	10
Clay	deleterious	10
Decomposed volcanics	deleterious	10
Slates	deleterious	10
Talc–gypsum	deleterious	10
Iron formations (very soft)	deleterious	10
Sibley formation	deleterious	10

a revised version (Table 2; Bragg, 1986). The P.N. is the sum of the factors for each clast and can range between 100 and 1000. The lower the P.N. the higher the rock quality (e.g., a clean, hard unweathered granite would normally have a P.F. of 1, and a P.N. of 100, whereas a friable, soft shale would normally have a P.F. of 10 and a P.N. of 1000). The petrographic factor/number is usually affected by the degree of weathering (Table 3).

Table 2. Revised petrographic factors for some rock types

Rock type	Petrographic factor range	Usual factor
1. Sandstone	1-6	1
2. Shale	10	10
3. Mudstone	3-6	6
4. Siltstone	1-6	1
5. Conglomerate	1-10	6
6. Arkose	1-6	1
7. Argillite	3-6	6
8. Greywacke	1-6	1
9. Chert	1-3	1
10. Limestone	1-6	1
11. Dolomite	1-6	1
12. Quartzite	1-6	1
13. Granite	1-6	1
14. Gabbro	1-6	1
15. Diorite	1-6	1
16. Granite–diorite series	1-6	1
17. Felsic volcanics	1-6	1
18. Mafic volcanics	1-6	1
19. Intermediate volcanics	1-6	1
20. Felsic–mafic volcanics	1-6	1
21. Pyroclastics	3-6	3
22. Metavolcanics	3-6	3
23. Gneiss	1-6	3
24. Schist	3-10	6
25. Phyllite	6-10	6
26. Marble	1-6	1
27. Slate	10	10
28. Amphibolite	6-10	6
29. Ultramafic	6-10	6
30. Metasediments	1-6	3
31. Iron formation	6-10	6
32. Drift deposits	Any or all of the above	Any or all of the above

Table 3. Effect of weathering on petrographic factors

Petrographic factor	Weathering grade	Final petrographic factors
1	1, 2	1,2
	3	3,4,5
	4, 5	6,7,8,9
	6	10
3	1, 2	3,4,5
	3, 4	6,7,8,9
	5, 6	10
6	1, 2	6,7,8,9
	3, 4, 5, 6	10
10	1, 2, 3, 4, 5, 6	10

LABORATORY INVESTIGATION

During the on-site field investigation, selected rock samples, ranging from 14 to 45 kg, were taken for laboratory

Table 4. Petrographic number ranges of different rock units found in the Mosquito Cove area

Group/Formation	Number of samples	Petrographic number range	Petrographic number < 160	Petrographic number > 160	Average petrographic number
Musgravetown	16	130-180	10	6	150
Bull Arm Formation	36	110-180	34	2	135

testing. The proposed test program includes the $MgSO_2$ soundness test (ASTM, 1983), which is used to indicate the durability of an aggregate in relation to weathering agents. The Los Angeles Abrasion test for small-size coarse aggregate (ASTM, 1989) and for large-size coarse aggregate (ASTM, 1989b), is used to measure the durability of an aggregate in relation to wear, impact and abrasion from other agents.

If the results of these tests are favourable, the sample will be tested for alkali-reactivity (ASTM, 1987b). This is a quick chemical test used to measure the percentage of dissolved silica after the sample has been immersed in a solution of 1 N sodium hydroxide for 24 hours at 80°C. The advandage of this test is that results are obtained rather quickly (1 day), however, the disadvandage is that the test is not completely reliable. The more reliable tests are the Motor Bar (ASTM, 1987a) and the Concrete Prism (CSA, 1977). However, the optiumum test which is being used is the NBRI test (Oberholser and Davies, 1986), which is a 14-day accelerated motar bar test.

DISCUSSION AND RESULTS

A total of 566 sites were visited and 322 samples collected. Of these, 142 samples are considered to be of potentially high-quality bedrock aggregate, 108 samples are of potentially marginal quality and 72 samples were considered to be of poor quality.

In the Bull Arm—Mosquito Cove areas, where 57 sites were visited and 52 samples collected (Table 4), the mafic volcanic rocks and flow-banded rhyolite of the Bull Arm Formation are considered to be of high quality (fresh, hard and competent) for concrete construction; and the acidic and mafic tuffs of the Bull Arm Formation and sandstones and siltstones of the Musgravetown Group are considered to be of marginal and poor quality for concrete construction, but may be of sufficent quality for asphalt and road construction. Of the 52 samples collected, 20 samples are considered to be of high quality (P.N. less than 150); these are mainly mafic and acidic volcanic rocks from the Bull Arm Formation, 18 samples are considerd to be of marginal quality (P.N. range from >150 to 350); these are mainly acidic and mafic tuffs from the Bull Arm Formation and sediments from the Musgravetown Group, 14 samples are considered to be of poor quality (P.N. greater than 350); these are mainly altered versions of the above rock types from the Bull Arm Formation and Musgravetown Group.

In central Newfoundland, 509 sites were visited and 270 samples were collected (Table 5). Of the 270 samples collected, 122 samples are considered to be of high quality (P.N.< 150) for use in concrete and asphalt. These are mainly igneous rocks (granites, diorites, gabbros, acidic and mafic volcanics) of the Topsails, Burlington, Dunamagon, Loon Bay, Halls Bay and Cape Brule Porphyry intrusives, the Robert's Arm, Springdale, Buchans, Mic Mac Lake, Flatwater Pond, Pacquet Harbour, Lushs Bight, Cape St. John and Snooks Arm groups and of the Betts Cove Complex and Lawrenceton Formation. Ninety samples are considered to be of marginal quality (P.N.>150 to 350), these are mainly found in the Sansom, Golden and Point Leamington greywackes and the New Bay Formation and from metmorphosed and moderatly weathered versions of the igneous rocks, which are listed above in the high-quality category. Fifty-eight samples are considered to be of low quality (P.N.>350), these are all metamorphic rocks (schists, pelites, psammites) of the Birchy Complex, East Pond Metamorphic suite, Dunnage Melange, Rattling Brook, Old House and White Bay groups, and of the Garden Cove and Pigeon Island formations.

CONCLUSIONS

The bedrock aggregate potential of the Bull Arm—Mosquito areas is high for road construction material (asphalt aggregate, Class A and B material), because of the physical properties (hardness, freshness and competencey) of the rock. However, when examining bedrock aggregate for concrete use, the chemical properties (alkali-aggregate reactivity) of the rock has also to be taken into consideration. Five samples from the area were taken for alkali-reactivity testing and the results are shown in Table 6. The results show that the basalts and rhyolite from the area are considered to be non-reactive, whereas the sandstone and tuffs in the area are considered to be reactive.

In central Newfoundland, bedrock-aggregate potential is high, especially among the igneous rocks, when they are fresh and hard. The sedimentary and metamorphic rocks of the area are considered to range from marginal to poor quality. It must be stressed that the above are only preliminary results and that further sampling and testing is essential to substantiate the quantity and quality of bedrock in both areas.

ACKNOWLEDGMENTS

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Table 5. Petrographic number ranges of different rock units found in the central Newfoundland field area

Group/Formation	Number of samples	Petrographic number range	Petrographic number <160	Petrographic number >160	Average petrographic number
Lawrenceton Formation	8	130-210	3	5	168
Robert's Arm Group	22	120-230	11	11	175
Topsails Granite	3	110	3	0	110
Springdale Group	9	125-210	3	6	165
Flatwater Pond Group	7	135-310	3	4	185
Betts Cove Complex	8	110-155	8	0	125
Birchy Complex	4	210-330	0	4	250
Rattling Brook Group	32	115-450	5	27	290
Old House Group	17	230-310	0	17	260
Garden Cove Formation	3	220	0	3	220
Pigeon Island Formation	3	210-270	0	3	240
White Bay Group	6	255	0	6	255
Pacquet Harbour	15	110-310	10	5	121
Dunamagon Granite	4	110	4	0	110
Cape Brule Porphyry	16	110-120	16	0	115
Cape St. John Group	29	110-135	29	0	120
Burlington Granodiorite	16	110-215	13	3	130
Loon Bay Batholith	6	115-125	6	0	120
Snook's Arm Group	3	125-155	3	0	135
East Pond Metamorphic Suite	9	215-350	0	9	265
Buchans Group	13	110-120	13	0	117
Golden Conglomerate	6	175	0	6	175
Sansom Greywacke	7	110-130	7	0	120
Dunnage Melange	9	110-350	2	7	260
Halls Bay Pluton	4	115	4	0	115
New Bay Formation	11	115-190	5	6	161
Point Leamington Greywacke	9	115-600	3	6	210
Lush's Bight Group	21	110-375	11	10	185

Table 6. Results of alkali-aggregate reactivity tests on representative rock samples in the Bull Arm area

Rock Type	% expansion in 14 days*	Comments
Tuff	0.365	Reactive
Basalt	0.020	Non-reactive
Basalt	0.029	Non-reactive
Rhyolite	0.078	Non-reactive
Sandstone	0.405	Reactive

*Note: Expansion > 0.15 percent at 14 days is considered deleterious and thus alkali-reactive.

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REFERENCES

American Society for Testing and Materials (ASTM)

1983: Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate. Annual ASTM standards, C88-83.

1985: Standard practice for petrographic examination of aggregate for concrete.

1986: Standard descriptive nomenclature for constituents of natural mineral aggregates.

1987a: Standard test method for potential alkali reactivity of cement-aggregate combinations (mortar-bar method). Annual ASTM standards, C227-87.

1987b: Standard test method for potential reactivity of aggregates (chemical method). Annual ASTM standards, C289-87.

1989a: Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine. Annual ASTM standards, C131-89.

1989b: Standard test method for resistance to degradation of large-size coarse aggregate by abrasion and impact in the Los Angeles machine. Annual ASTM standards, C535-89.

Bragg, D.J.
1986: Reconnaissance study of bedrock aggregate for offshore and industrial use. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 297-301.

1989: Reconnaissance assessment of potential bedrock aggregate. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 221-227.

Bragg, D.J. and Norman, G.
1988: Aggregate potential of bedrock on the Avalon Peninsula. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 367-372.

Canadian Standards Association
1977: Test method for alkali-aggregate reaction. National Standard of Canada CAN 3-A23.2-M77, Canadian Standards Association, A23.2-14A.

Hibbard, J.
1983: Geology of the Baie Verte Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Memoir 2, 279 pages.

King, A.F.
1988: Geology of the Avalon Peninsula, Newfoundland (parts of 1K, 1L, 1M, 1N and 2C). Newfoundland Department of Mines, Mineral Development Division, Map 88-01.

Kean, B.F., Dean, P.L. and Strong, D.F.
1981: Regional geology of the Central Volcanic Belt of Newfoundland. *In* The Buchans Ore Bodies: Fifty Years of Geology and Mining. *Edited by* E.A. Swanson, D.F. Strong and J.G. Thurlow. Geological Association of Canada, Special Paper 22, pages 65-78.

Oberholster, R.E. and Davies, G.
1986: An accelerated method for testing the potential alkali-reactivity of siliceous aggregates. *In* Cement and Concrete Research, Volume 16, pages 181-189.

Ricketts, M.J. and McGrath, J.
1990: Granular aggregate-resource mapping of the Gander Lake (NTS 2D/15), Gander River (NTS 2E/2) and Comfort Cove–Newstead (NTS 2E/7) map areas. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 65-75.

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DETAILED AGGREGATE-RESOURCE ASSESSMENT PROJECT, INSULAR NEWFOUNDLAND

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Mineral Resource Management Branch

ABSTRACT

This report details the results of the 1990 field program to assess the aggregate-resource potential of (1) Isthmus of Avalon, (2) Northern Arm, (3) Grand Falls, (4) Kings Point, (5) Pasadena–South Brook, (6) Raleigh, (7) Holyrood quarry area, and (8) Shoal Harbour Pond.

On the Isthmus of Avalon, the study was successful in identifying an area of sand and gravel, which could supply aggregate for the construction of the offshore gravity-based structures (GBS) at Great Mosquito Cove. At Raleigh, Kings Point and Northern Arm, aggregate studies were undertaken to better define the high-quality aggregate sites, so they can be protected from conflicting land uses. Studies conducted at Grand Falls, Shoal Harbour Pond and Holyrood identified additional sources of high-quality aggregate material, whereas at Pasadena, the study failed to locate any high-quality aggregate material suitable for use in asphaltic pavement and/or concrete.

During the study, 133 sand, gravel and till samples were collected and analyzed.

INTRODUCTION

In 1982, a long-term program of detailed aggregate-resource assessments was initiated to provide data on the aggregate-resource potential of areas where municipal and other plans are being developed, or where detailed aggregate information is required to meet a specific need (e.g., highway construction). The existing aggregate-resource database (Kirby *et al.*, 1983) has been useful in defining potential land-use conflict areas, but it does not provide detailed information on the aggregate resources themselves, which are necessary to resolve these conflicts. Detailed studies, such as those outlined in this report, should provide the necessary (sieve and petrographic analyses) information required to identify high-quality aggregate reserves or to resolve various land-use conflicts, (e.g., housing development over a high-quality aggregate deposit).

The 1990 field program was conducted in eight areas of the province; (1) Isthmus of Avalon, (2) Northern Arm, (3) Grand Falls, (4) Kings Point, (5) Pasadena–South Brook, (6) Raleigh, (7) Holyrood quarry area, and (8) Shoal Harbour Pond (Figure 1).

FIELD PROGRAM

Potential areas for detailed assessment were selected based on a review of existing aggregate-resource and surficial data, and on the analysis of 1:50,000- and 1:12,500-scale aerial photographs.

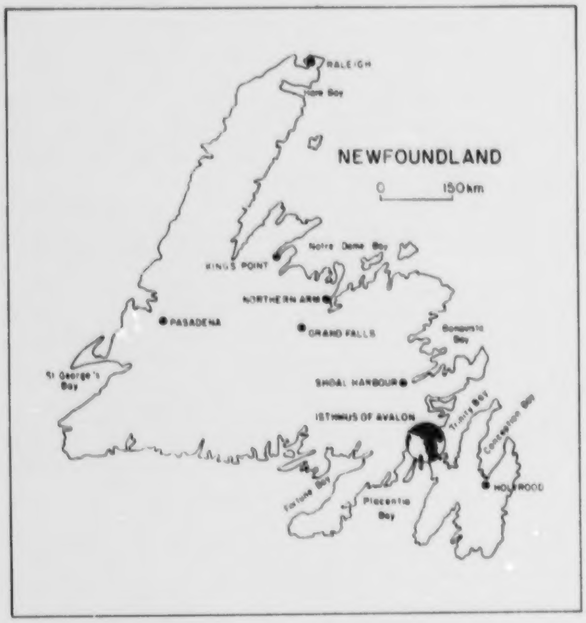


Figure 1. *Location of study area.*

The first phase of field work involved driving along all roads and trails, to verify or update data on previously sampled and/or unsampled surficial deposits (Kirby *et al.*, 1983). Foot traversing was conducted in areas of potential quarry development and sites were selected for sampling.

Backhoe test-pits were used, where possible, to obtain samples used to determine the extent, quantity and quality of the aggregate deposit. Natural exposure or shallow hand-dug pits were used to sample the underlying aggregate material, where a backhoe was not or could not be used.

DATA ANALYSIS AND STORAGE

During the 1990 field program, 133 granular, aggregate samples were collected. Samples containing greater than 8-mm-size material were sieved through a bank of 4 sieves (63, 31.5, 16 and 8 mm) in the field. About 100 pebbles from the 16 and 31.5 mm fractions were retained for field rock-type and petrographic analysis using procedures outlined by Bragg (1986). This analysis determines the petrographic rank for the various aggregate samples, which is a measure of their suitability for use as a source of aggregate. The lower the number, the higher the quality of the aggregate material (e.g., 100 best, 1000 worst). A split of the finer than 8 mm fraction was retained for laboratory sieving through a nest of sieves (8, 4, 2, 1, 0.5, 0.25, 0.125 and 0.062 mm) following procedures outlined by Kirby *et al.* (1983).

All of the sieve and petrographic data have been stored in a computer for ease of retrieval and are available upon request from the author at the Department of Mines and Energy. Deposit quality observations are based on standards followed by the Newfoundland Department of Works, Services and Transportation (Specification Book, 1987), which are based on ASTM standards for granular materials. The highest petrographic number permitted for use in concrete is 130, whereas for asphaltic pavement, the number is 135.

ISTHMUS OF AVALON

The objective of this part of the study was to identify sources of aggregate material close to the Bull Arm–Great Mosquito Cove area, which could be used in the construction of the site infrastructure, and the offshore gravity-based structure (GBS). The study was divided into two parts. The first part involved the sampling of the bedrock throughout the Bull Arm area to assess its potential to supply crushed bedrock aggregate (Bragg, *this volume*). The second part involved a surficial aggregate survey within a 30 km radius of Great Mosquito Cove (Figure 2). Ricketts (1986), conducted an aggregate-resource mapping and sampling program throughout the Placentia Bay area. Large reserves of high-quality sand and gravel have been identified in the Swift Current area and at Black River Point, North Harbour Point and Woody Island (Ricketts, 1989). These sites have the potential to supply the required volumes of sand needed to complete the offshore-production platform project but the cost of transporting this material to the Trinity Bay, Bull Arm construction site would be high. This study concentrated on locating sources of sand and gravel closer to the GBS construction site. A number of areas were field checked but the only source of aggregate material identified within the Bull Arm area is at North West Brook (Figure 2). The deposit is a deltaic deposit composed of stratified sand and gravel, averaging a thickness of about 10 m. The surface is overlain by 1 to 4 m of bog. Nine samples were collected from existing quarry faces and from shallow hand-dug test pits. The results of the sieving show the deposit to be a pebble–cobble gravel having an average grain-size distribution of 67 percent gravel, 32 percent sand and 1 percent silt-clay. The average petrographic number obtained from seven of the samples was 191 having a range of 121 to 306. The presence of conglomerate and ultramafic rocks, which is as high as 15 percent in some samples, results in petrographic numbers in excess of minimum standards. Further testing is needed to determine the suitability of this deposit as a source for aggregate. The total reserves are estimated at greater than 1,000,000 m³.

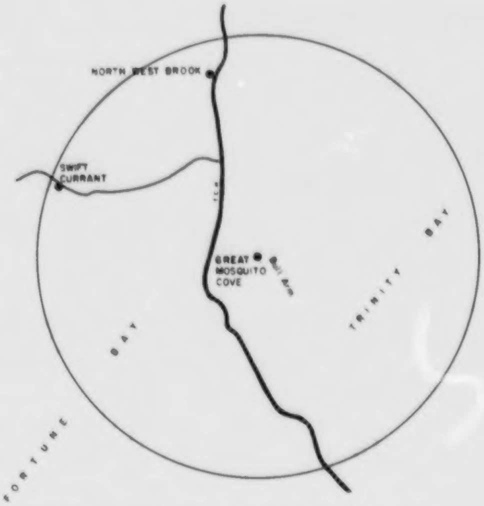


Figure 2. *Isthmus of Avalon study area.*

NORTHERN ARM

In 1990, an excavator testpitting and sampling program was conducted in a glaciofluvial terrace deposit situated within the town of Northern Arm, to determine the extent of the high-quality gravel deposit (Kirby *et al.*, 1983). The quarry, which is situated within the community, is controversial because it has high vertical faces and has not been rehabilitated in those areas that have been mined. The testpitting program was designed to outline the complete extent of the deposit, and to allow for the development and implementation of a detailed extraction and rehabilitation plan for the area.

Ten backhoe test-pits were dug to an average depth of 3.8 m. The results of the sieve analysis of samples collected from six test pits, gave an average grain-size distribution of 57 percent gravel, 42 percent sand and 2 percent silt-clay, and an average petrographic number of 137. One test-pit exposed sand having a particle-size distribution of 98 percent sand and 2 percent silt-clay. Two unsampled pits revealed silt-clay, and one other pit intersected till under 0.4 m of sandy gravel. A map showing the extent of the deposit was produced from the information obtained from the test-pits.

GRAND FALLS

This site is located approximately 23 km west of Grand Falls and 1 km south of the Trans-Canada Highway along the banks of the Exploits River (Figure 3). The deposit was located in 1989 (Kirby, 1990) and samples collected from shallow hand-dug pits indicated high-quality sand and gravel. The deposit is subdivided into two areas based on terrain type. Area 1 is a flat, glaciofluvial terrace deposit having a widely spaced black spruce vegetation cover (Plate 1). A total of 14 backhoe test-pits were dug to an average depth of 3.5 m. The deposit is composed of a pebble–cobble gravel having an average grain-size distribution of 67 percent gravel, 32 percent sand and less than 1 percent silt-clay, and an average petrographic number of 216. The relatively high petrographic number is due to the presence of moderately weathered conglomerate and to a lesser extent, weathered acidic volcanic rocks. Conglomerate comprises, on average, 15 percent of the pebble content. Detailed testing, which included Los Angeles abrasion and alkali reactivity tests, will have to be performed to determine the suitability of this deposit as a source of aggregate for concrete and/or asphaltic pavement.

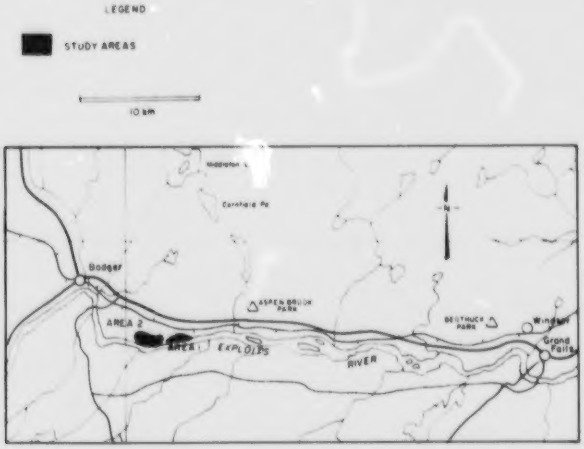


Figure 3. *Grand Falls study areas.*

Area 2 is located to the west of Area 1 (Figure 3) and is composed of a series of forested ridges, which represent interfluves between drainage channels cut through a glaciofluvial terrace, during the Holocene. Eighteen backhoe test-pits were dug into the ridges and into the intervening channels to an average depth of 3.4 m. This deposit is a pebble–cobble gravel having an average grain-size distribution of 71 percent gravel, 28 percent sand and less than 1 percent silt-clay, and an average petrographic number of 198. The relatively high petrographic number is due to the presence of moderately weathered sedimentary rocks, which include siltstone and fine to medium sandstone that comprises 30 to 35 percent of the pebble fraction. In some samples, moderately weathered acidic volcanic rocks cause an increase in the petrographic number. Further testing is required on this deposit to determine its suitability for concrete or asphaltic pavement.

Plate 1. *Widely spaced black spruce is the typical vegetation cover encountered on the glaciofluvial terrane in Area 1, west of Grand Falls.*

KINGS POINT

During 1989 and 1990, an increasing number of crown land applications have been received for land in the area of the deltaic sand and gravel deposits at Kings Point. A subsequent inspection revealed that large areas of the delta south of Paddy's Brook have already been sterilized due to conflicting land uses (e.g., community expansion) (Figure 4). No work was done north of Paddy's Brook because there are presently no conflicting land uses in this area. The aim of this study is to map the conflicting land uses and identify areas that should be set aside for future aggregate extraction.

The Kings Point delta is a glaciomarine delta formed during deglaciation (Tucker, 1974). Samples collected from natural and man-made exposures, showed the delta is composed of well-sorted sand and gravel (Plate 2) having an average grain-size distribution (from twelve samples collected) of 60 percent gravel, 39.5 percent sand and 0.5 percent silt-clay and an average petrographic number of 110. The grain-size distribution and excellent petrographic characteristics make this deposit a source of sand and gravel for all high-quality aggregate uses. Figure 4, shows the locations of the existing land-use conflicts and the areas that should be set aside as future aggregate sources.

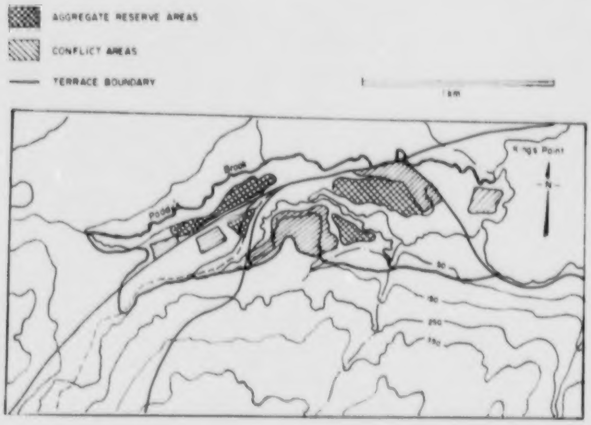

AGGREGATE RESERVE AREAS
CONFLICT AREAS
TERRACE BOUNDARY
1 km
Brook
Kings Point
N
90
150
250

Figure 4. *Land-use within the Kings Point study area.*

Plate 2. *Foresets of well sorted sand and gravel in a quarry at Kings Point.*

PASADENA–SOUTH BROOK

At this site, work concentrated on locating sources of high-quality sand and gravel for use in the reconstruction of the Trans-Canada Highway through the Pasadena area. Previous aggregate-resource mapping within the Pasadena Municipal planning area (Kirby, 1985) has shown that the community of Pasadena is built over an extensive sand and gravel deposit. Several potential aggregate sites were identified, however, due to their poor petrographic characteristics, they are unsuitable for use as concrete or asphaltic pavement, but could be used to produce crushed road gravel.

In 1990, field work concentrated on locating high-quality aggregate in the South Brook River valley, a north-south trending valley between Grand Lake and Deer Lake. (Figure 5). The delta on which Pasadena is sited was formed as South Brook entered a much higher Deer Lake during deglaciation (Batterson and Taylor, 1990). Sampling along the western side of the valley was confined to existing natural and man-made exposures. The majority of the deposits are composed of silty tills or colluvium. Gravel deposits located were a raised delta at 136 m a.s.l., (Batterson and Taylor, 1990), and a similar gravel deposit at the same elevation, but located near Northern Harbour, Grand Lake; the former is composed of stratified sandy gravel. Both of these deposits are small and have poor petrographic characteristics having petrographic numbers of 225 and 455, respectively.

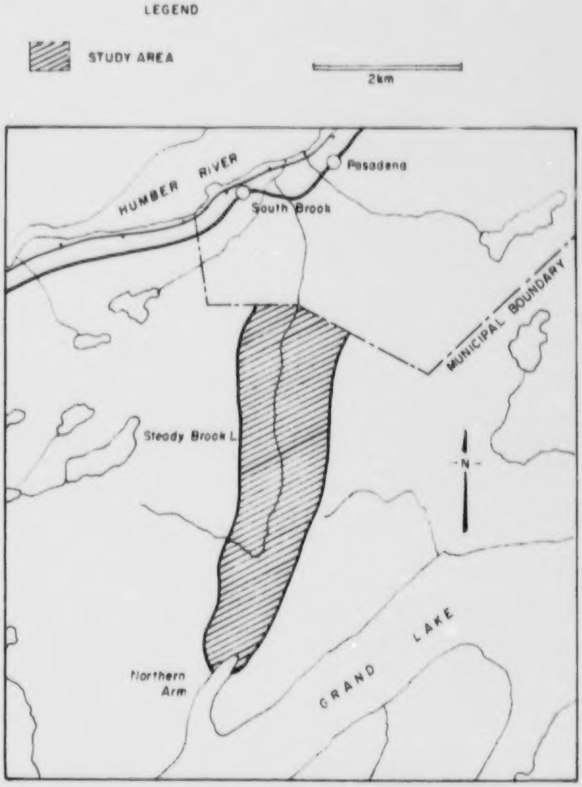

LEGEND
STUDY AREA
2km
HUMBER RIVER
Pasadena
South Brook
MUNICIPAL BOUNDARY
Steady Brook L.
N
Northern Arm
GRAND LAKE

Figure 5. *Pasadena–South Brook study area.*

Most of the sampling was conducted on the east side of South Brook River valley, where a number of distinct terrace levels were identified and testpitted using a tracked excavator. Nineteen test-pits were dug to an average depth of 3.6 m. Seven sites between 65 and 105 m a.s.l., revealed fine sand over silt-clay (Plate 3), having a silt-clay content ranging from 60 to 93 percent. The remaining twelve test-pits were dug between 105 and 165 m a.s.l. The majority of these pits were dug parallel to the river over a distance of 1 km, and crossed two incised stream channels. Two distinct types of sediment were identified. On the interfluves between the channels, sampling revealed a silty till having a grain-size distribution of 32 percent gravel, 51 percent sand and 17 percent silt-clay, and an average petrographic number of 339. Samples collected in areas affected by the stream channels have revealed a gravelly diamicton interpreted as a washed till, with an average grain-size distribution of 46 percent gravel, 50 percent sand and 4 percent silt-clay, and an average petrographic number of 293. The poor petrographic characteristics in both areas are the result of metasedimentary rocks, which compose up to 40 percent of the pebble fraction of the samples collected. These deposits could be used as a source of fill or crushed gravel, but would not be suitable as a source of aggregate for asphaltic pavement or concrete.

Plate 3. *Stratified sand over silty sand over clay in a test pit at Steady Brook.*

RALEIGH

The original inventory of the aggregate-resources project (Kirby *et al.*, 1983) identified a large area of high-quality aggregate within the planning area (Figure 6). Since the original inventory was completed, large areas within the zone have been sterilized due to community expansion, and the new municipal plan called for the establishment of a housing sub-division within the aggregate zone. Therefore, this study was undertaken to redefine the aggregate zone.

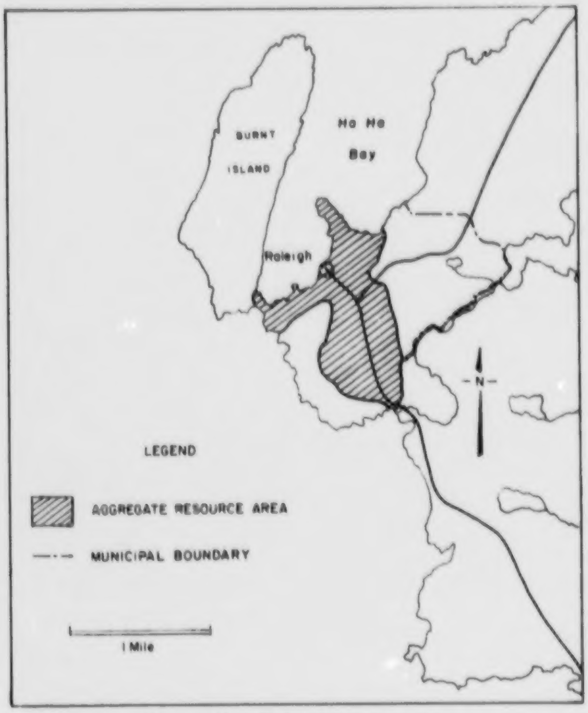


Figure 6. *Raleigh study area.*

The area identified as high-quality aggregate (Figure 6) is covered by a thin veneer (less than 2 m) of dark brown to black marine sandy gravel, having numerous rock outcrops and thicker deposits of gravel in the hollows between the outcrops. Grain-size distribution of three samples collected and analyzed show an average of 49 percent gravel, 50 percent sand, and less than 1 percent silt-clay, and an average petrographic number of 183. This material is only used as a source of fill mainly because it is a thin and discontinuous deposit and because of its colour. As a result of this, only an area of 300 m around the existing quarries will be reserved exclusively for quarry activity.

The main source of concrete aggregate are thin (<2.5 m) raised marine beach sediments and talus deposits eroded from the steep vertical cliffs on Burnt Island (Figure 6). The raised marine beach sediments are found in shallow depressions in the bedrock surface scattered throughout Burnt Island, whereas the talus is found at the base of the steep cliff mainly at the northern end of the Island (Plate 4). Sieve

Plate 4. *Talus used in the production of concrete on Burnt Island.*

analysis of the raised marine deposits give an average grain-size distribution for two samples of 64 percent gravel, 35 percent sand and less than 1 percent silt-clay, and an average petrographic number of 100. The talus deposits have a grain-size distribution from two samples of 92 percent gravel, 6 percent sand and 2 percent silt-clay, and an average petrographic number of 100. These deposits are derived from limestone of the Lower Ordovician St. Georges Group and the Middle Ordovician Table Head Group (Howse, 1990). Both of these sources, when combined, would make an excellent quality aggregate for most uses.

HOLYROOD

This deposit is located in a north-south oriented valley between Butter Pot Pond and Fenelons Pond, south of Holyrood (Figure 7). The area is composed of hummocks, which range between 5 and 10 m in height and have shallow bogs between the ridges. The hummocks are generally composed of sandy till with scattered boulders, and some sand and gravel lenses. This deposit is presently the site of two large quarry operations, which supply concrete aggregate to the St. John's and area market (Figure 7). Kirby (1990) conducted a testpitting program, east and south of the existing quarries and, identified additional high-quality reserves (Figure 7).

The present program sampled the area to the north of the existing quarry. Samples obtained from 14 excavator dug test-pits have an average depth of 3.1 m. The average grain-size distribution for the fourteen samples collected was 57 percent gravel, 37 percent sand and 6 percent silt-clay, and an average petrographic number of 109. These results are consistent with other samples collected in the area and extend the limits of the known resource.

SHOAL HARBOUR POND

A testpitting program using a crawler excavator was conducted at Shoal Harbour Pond, approximately 10 km north of Clarenville (Figure 8). The area was first identified during the Inventory of Aggregate Resources Program (Kirby *et al.*, 1983) and comprises an esker complex area, which has numerous esker ridge segments and hummocks up to 15 m in height (Plate 5); the area was heavily used, in 1989, for aggregate in the reconstruction of the Trans-Canada Highway, west of Clarenville. The aim of this program was to identify areas of gravel adjacent to the existing quarries suitable for use in concrete production. The testpitting was confined to an area southwest of the existing quarries, an area composed of a series of steep-sided esker ridges covered by a mature stand of widely spaced black spruce or cutover.

Five test-pits were dug and sampled in the ridge area to an average depth of 4 m, revealing a sandy pebble gravel having an average grain-size distribution of 55 percent gravel, 44 percent sand and less than 1 percent silt-clay. Petrographic analysis has not yet been completed on these samples, but samples collected in the same area in 1979 have an average petrographic number of 155 (Kirby *et al.*, 1983). Further physical and chemical testing will have to be conducted on the deposit to determine its suitability as a source of concrete aggregate.

SUMMARY

During the 1990 field season, 133 samples were collected and analyzed from eight field areas across the island. The summary results are as follows.

(1) Isthmus of Avalon—the study was successful in identifying an area of sand and gravel, which could be used to supply aggregate material for use in the construction of a GBS at Great Mosquito Cove.

(2) Northern Arm—a testpitting program was conducted to determine the extent of an aggregate deposit within the town. The information was required so that a detailed extraction and rehabilitation plan can be developed for inclusion in the town's Municipal Plan.

(3) Grand Falls—a testpitting program was conducted 23 km west of Grand Falls and was successful in verifying the existence of a high-quality aggregate deposit, with the potential to supply high-quality aggregate to the Grand Falls and area market.

(4) Kings Point—work in this area concentrated on identifying areas of high-quality aggregate within the Kings Point delta system, which have not been sterilized due to conflicting land uses.

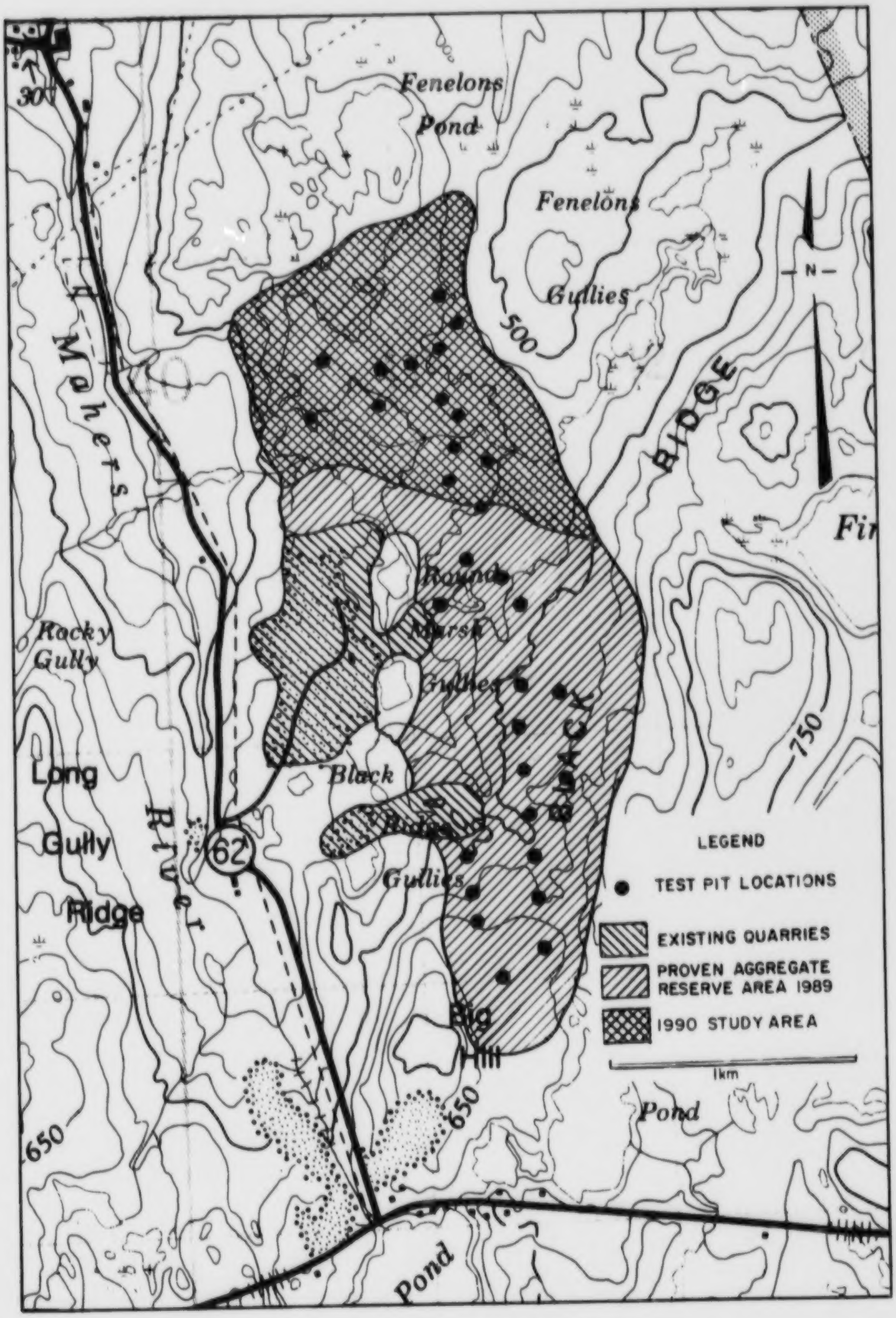

30
Fenelons
Pond
Fenelons
Gullies
N
500
RIDGE
Fir
Mahers
River
Round
Marsh
Gullies
Rocky
Gully
Long
Gully
Ridge
Black
Ridge
Gullies
BLACK
750
62
LEGEND
TEST PIT LOCATIONS
EXISTING QUARRIES
PROVEN AGGREGATE RESERVE AREA 1989
1990 STUDY AREA
1km
Big
Pond
650
650
Pond

Figure 7. *Holyrood study area.*

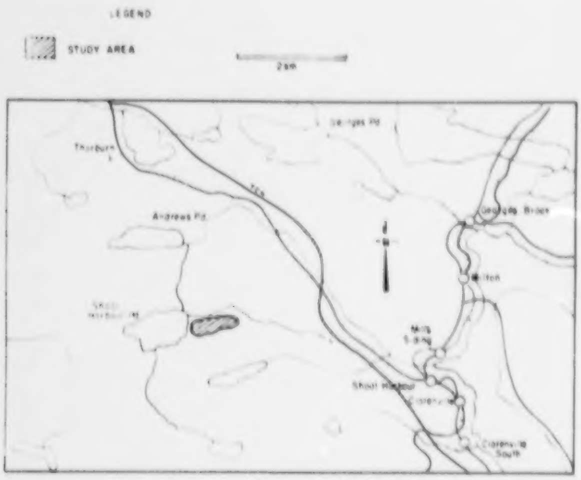


Figure 8. *Shoal Harbour Pond study area.*

Plate 5. *Esker complex area near Shoal Harbour Pond.*

(5) Pasadena–South Brook–work conducted mainly in the South Brook River valley failed to locate large reserves of high-quality aggregate suitable for use in the re-construction of the Trans-Canada Highway through the Pasadena area.

(6) Raleigh–work in this area concentrated on redefining the aggregate-resource zones within the Raleigh municipal planning area. This work led to the elimination of the aggregate-resource zones within the planning area and the identification of aggregate resources suitable for use in concrete on Burnt Island.

(7) Holyrood–a testpitting program conducted in the area to the north of the existing quarries has verified the continuation of this deposit in that direction.

(8) Shoal Harbour Pond–a testpitting program conducted to the southwest of the existing quarries was successful in identifying additional sources of sand and gravel suitable for use in the production of concrete.

ACKNOWLEDGMENTS

Christine Blackwood is thanked for her prompt results from the Laboratory and Harold Hannon is thanked for drafting the figures. This report was critically reviewed by Martin Batterson.

REFERENCES

Batterson, M.J. and Taylor, D.M.
1990: Glacial history of the Humber River Basin. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 1-6.

Bragg, D.
1986: Reconnaissance study of bedrock aggregate for offshore and industrial use. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 297-301.

This volume: Bedrock aggregate surveys in the Bull Arm–Mosquito Cove areas, Trinity Bay, and central Newfoundland.

Howse, A.F.
1990: Limestone assessment on Newfoundland's west coast and Northern Peninsula. *In* Review of Activities for 1990. Newfoundland Department of Mines and Energy, Geological Survey Branch, pages 80-81.

Kirby, F.T.
1985: Detailed aggregate assessment project–insular Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 201-203.

1990: Detailed aggregate–resource assessment project, Newfoundland and Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 19-26.

Kirby, F.T., Ricketts, R.J. and Vanderveer, D.G.
1983: Inventory of aggregate resources in Newfoundland and Labrador; information report and index maps. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 83-2, 36 pages.

Ricketts, M.J.
1986: Detailed aggregate mapping related to concrete platform. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 291-296.

1989: Swift Current aggregate resource map (NTS 1M/16). Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 8934.

Specifications Book
1987: Newfoundland Department of Transportation Tendering Section, St. John's, Form 904, 8 pages.

Tucker, C. M.
1974: A series of raised Pleistocene deltas in Halls Bay, Newfoundland. Maritime Sediments, Volume 10, pages 1-7.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 29-44

QUATERNARY GEOLOGY OF THE SPRINGDALE MAP AREA (12H/8)

David G.E. Liverman, Sharon Scott and Howard Vatcher
Terrain Sciences

ABSTRACT

The Springdale area is located in north-central Newfoundland (NTS 12H/8). The landscape and surficial deposits of the area have been strongly affected by the last glaciation. Ice flow over the south and west of the map area involved a single major flow, from the Topsails, parallel to the major valleys converging on Hall's Bay. Close to the coast, a two-phase ice-flow history is found, in which the initial flow was parallel to Hall's Bay (northeasterly), followed by a subsequent flow toward the bay. In coastal and low-lying areas, much of the sediment was deposited by marine processes during periods of raised postglacial sea level. Inland, a thick till cover was deposited mainly by a combination of basal melt-out and supraglacial melt-out processes. Much of the surface sediment has been modified by meltwater. Several sites show multiple diamictons, and these are interpreted as evidence of a late re-advance of Late Wisconsinan ice. Ice-wedge casts in the Indian Brook valley indicate a periglacial climate following initial deglaciation, possibly related to this re-advance.

INTRODUCTION

The Springdale map area (NTS 12H/8) is located in north-central Newfoundland (Figure 1). It is an area of moderate interest with regard to mineral exploration; the pulp and paper industry is also active in the area, and considerable reforestation takes place. A knowledge of the physical properties and distribution of surficial sediment, as well as the regional Quaternary geological history is important in using drift-exploration techniques, in locating groundwater resources, in the siting of waste-disposal sites, in civil engineering work, in planning reforestation, in soil mapping, and in land-use planning.

BEDROCK GEOLOGY

The bedrock geology of the 12H/8 map area was mapped by Dean (1977), Kean (1977), Hibbard (1983), Swinden (1987), Coyle and Strong (1987), and Bostock (1988). The bedrock is dominated by the Silurian Springdale Group, which outcrops over most of the central part of the study area (Figure 2). It consists of subaerial volcanic and clastic rocks including basaltic and andesitic flows, pyroclastic rocks, silicic ash-flow tuffs, rhyolite domes, volcanic-derived debris flows and breccias, and fluvial red sandstones and conglomerates (Coyle and Strong, 1987). The northwestern boundary of the Springdale Group is formed by the northeast-trending Lobster Cove–Chanceport fault, and by the Topsails Granite. The Catchers Pond Group (intermediate to felsic volcanic rocks) is exposed between the parallel Lobster Cove and Green Bay faults (Kean, 1977). Northwest of the Green Bay fault, the Mic Mac Lake group consists of subaerial silicic volcanic and pyroclastic rocks, associated with minor sandstone and conglomerate. It is intruded by the Burlington Granodiorite (Hibbard, 1983, 1989). The area around Indian Pond is underlain by Carboniferous sandstones and conglomerates (Dean, 1977). The east part of the map area is underlain by the Robert's Arm Group, consisting of pillow lavas, agglomerate and breccia, and minor rhyolite flows, and the Sansom Greywacke. A number of plutonic intrusions are found in this area, including the mafic to intermediate Hall Hill Complex, the granitic Mansfield Cove Complex and Loon Pond pluton, the granitoid South Pond pluton, and the mafic to intermediate Twin Lakes Complex (Swinden, 1987).

Economic interest has been restricted to the Roberts Arm Group, which hosts the Gullbridge deposit to the south of the map area, as well as numerous minor occurrences of base metals. The Catchers Pond Group contains minor mineral occurrences and mineralized base-metal float, possibly hosted by this Group, has been found south of Indian Pond (Alley and Slatt, 1975).

PREVIOUS WORK

O'Donnel (1973) studied boulder trains originating from the Gullbridge mine site (south of the field area), and postulated two ice-flow phases of the same advance, an earlier northeastward flow shifting to a later northwestward movement. Alley and Slatt (1975) and Alley (1976) discussed the glacial geology and sediment dispersal in the Sheffield Lake–Indian Pond area. Measurement of striae suggested a dominant northeastward flow, but with indications of later eastward flow. They identified two tills, an 'upper grey till' and a 'lower red till' and interpreted both to be lodgment tills deposited by separate advances.

Grant (1973, 1986) mapped the 12H/8 map area and located striae suggesting a northeastward flow. Ice-flow indicators have also been mapped by Lundqvist (1965), Tucker (1973), and Bostock (1988). Their data suggest valley-parallel flow in the southern half of the map area, and complex flow in the coastal areas. Liverman and Scott (1990) described a

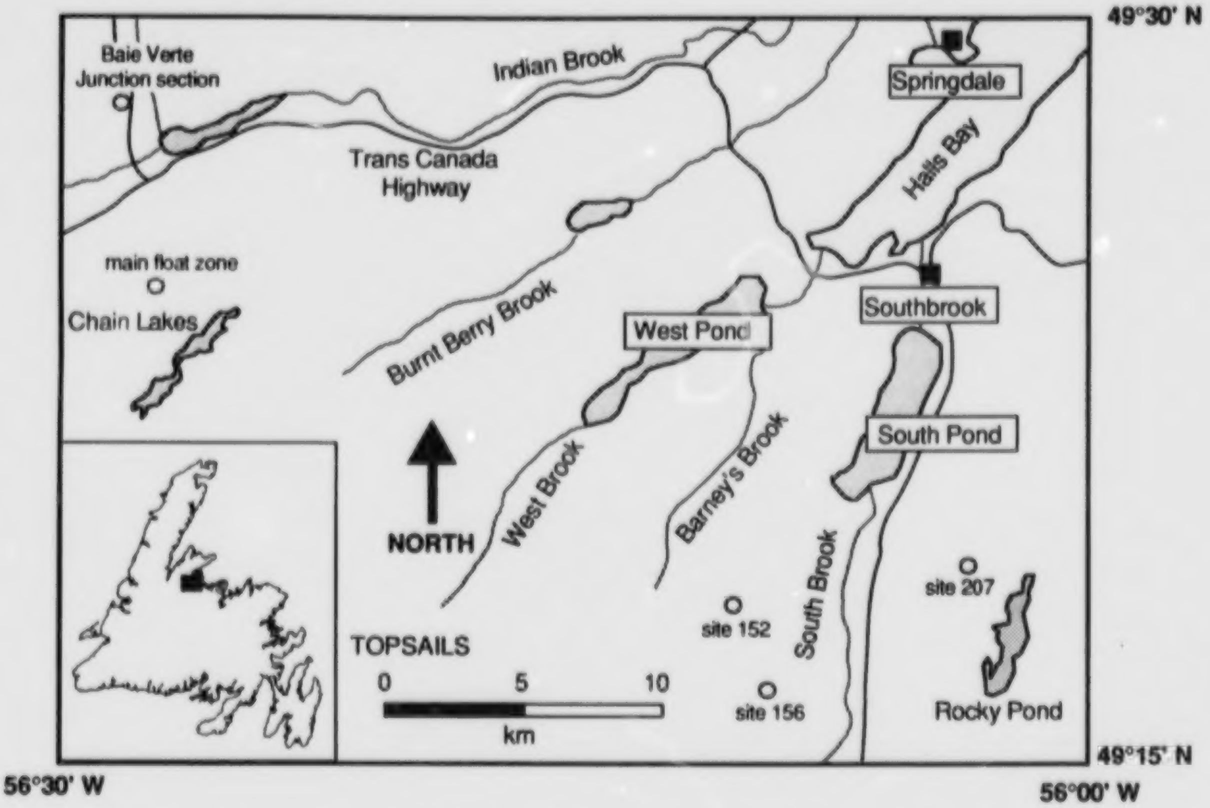

49°30' N
Baie Verte
Junction section
Indian Brook
Springdale
Trans Canada
Highway
Halls Bay
main float zone
Chain Lakes
Burnt Berry Brook
West Pond
Southbrook
South Pond
NORTH
West Brook
Barney's Brook
South Brook
site 207
site 152
TOPSAILS
0
5
10
km
site 156
Rocky Pond
49°15' N
56°30' W
56°00' W

Figure 1. *Location and main features of the 12H/8 map area. Main float zone refers to the area of mineralized float described by Alley and Slatt (1975).*

two-phase ice-flow history on the King's Point map area (adjoining the Springdale map area to the north), with an initial northeastward ice flow overprinted by a later eastward to southeastward flow toward Hall's Bay.

Grant (1973, 1986) and Tucker (1973, 1974) mapped and described extensive marine deposits in coastal areas, with a marine limit defined at 75 m.a.s.l. on the basis of sediment distribution. Vanderveer (1977) evaluated marine clay deposits south of Springdale with regard to pottery and brickmaking. These sediments are further described by Scott and Liverman *(this volume).*

FIELD METHODS

Access to the area is excellent due to the numerous logging roads built in the last thirty years. Most of these roads are still in good condition, and were traversed using truck or all terrain vehicle. Close to three-hundred sites were described in detail, including over 100 striation sites, and 16 backhoe pits. A total of 67 clast fabrics was obtained from diamictons exposed in sections and backhoe pits. Samples of matrix were analyzed for geochemistry and texture, and 80 to 120 pebbles were collected from diamictons to allow for clast lithology identification.

ICE FLOW

Over 100 striae sites were noted in the course of field work (see Liverman *et al.*, 1990 for locations). They suggest a relatively simple ice-flow history over the south and west parts of the map area, showing flow from the Topsails Hills, parallel to the major valleys of Indian Brook, Burnt Berry Brook, West Brook, Barney's Brook, and South Brook (Figure 3). This results in a pattern converging on Hall's Bay, which appears to have acted as a major conduit of ice away from adjacent central Newfoundland. Most multiple striation sites are found close to the coast (Plate 1) and indicate a two-phase ice-flow history, with initial flow, parallel to Hall's Bay (northeastward). Subsequent flow from the northwest side of the bay was eastward, but striae from the southeast side of the bay indicate late northwestward flow. Thus, late-stage local-ice-flow was toward Hall's Bay. Where clast fabrics from diamictons show strong unimodal orientations, generally, they parallel striations found in the same area (Liverman *et al.*, 1990).

Combining these results with other striation mapping in the area (Liverman and St. Croix, 1989a; Scott *et al.*, 1990; Liverman and Scott, 1990; St. Croix and Taylor, *this volume*) suggests that following initial flow from a major ice centre

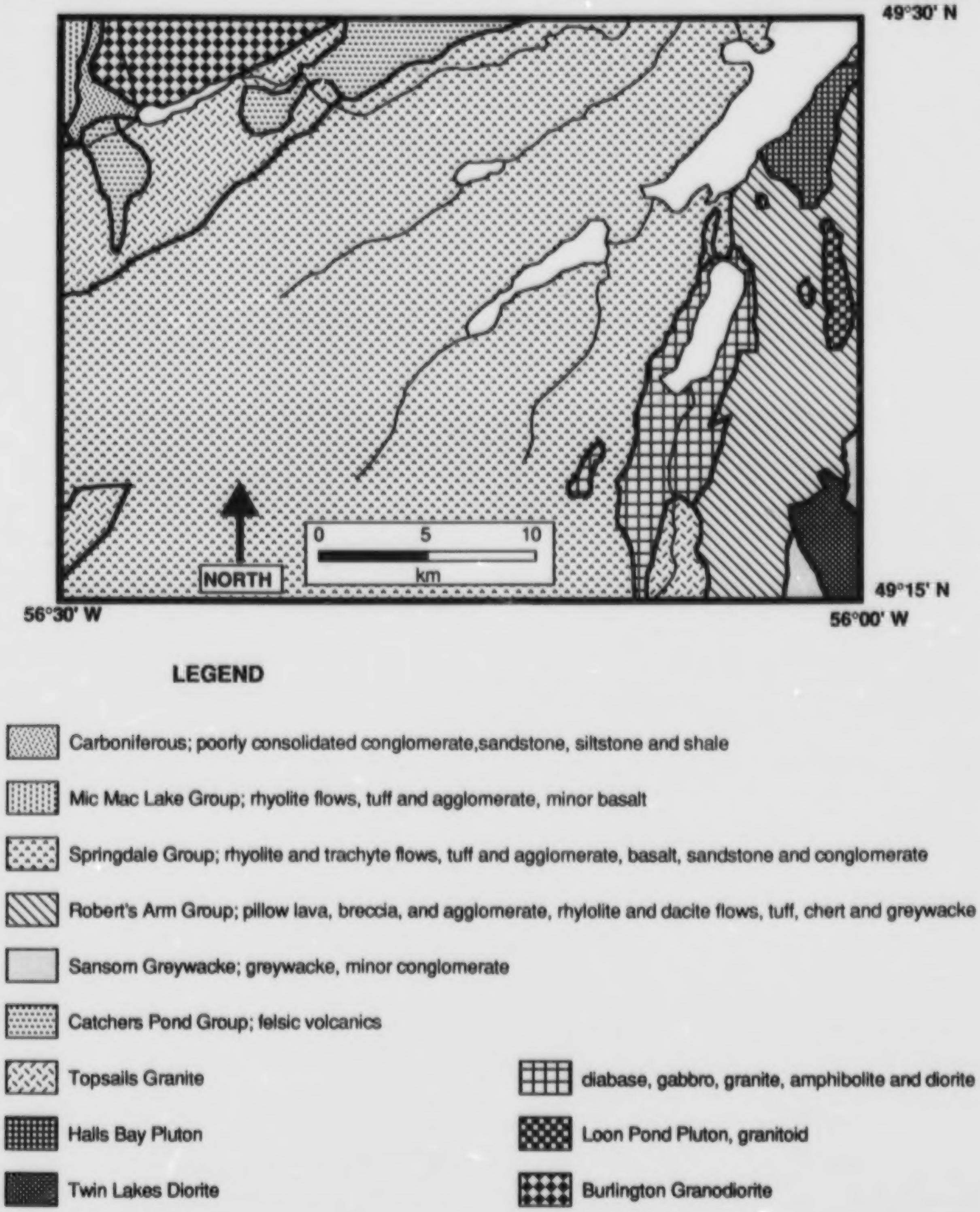

49°30' N
49°15' N
56°30' W
56°00' W
NORTH
0
5
10
km
LEGEND
Carboniferous; poorly consolidated conglomerate,sandstone, siltstone and shale
Mic Mac Lake Group; rhyolite flows, tuff and agglomerate, minor basalt
Springdale Group; rhyolite and trachyte flows, tuff and agglomerate, basalt, sandstone and conglomerate
Robert's Arm Group; pillow lava, breccia, and agglomerate, rhylolite and dacite flows, tuff, chert and greywacke
Sansom Greywacke; greywacke, minor conglomerate
Catchers Pond Group; felsic volcanics
Topsails Granite
Halls Bay Pluton
Twin Lakes Diorite
diabase, gabbro, granite, amphibolite and diorite
Loon Pond Pluton, granitoid
Burlington Granodiorite

Figure 2. *Bedrock geology, 12H/8 map area, adapted from Dean (1977), Kean (1977), Hibbard (1983), Coyle and Strong (1987), and Swinden (1987).*

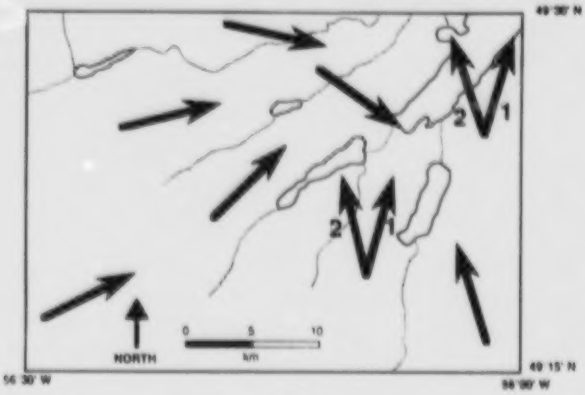


Figure 3. *Ice flow, Springdale map sheet. Arrows represent regional-flow directions deduced from numerous striation measurements, and numbers indicate age relationships (1 being oldest, 2 youngest).*

Plate 1. *Striated outcrop north of South Brook, showing preservation of a northward flow in the lee of a westward flow (towards Hall's Bay).*

located over the area of the Topsails, minor ice centres were established as deglaciation commenced. One such centre was located northwest of the map area. Flow from this centre was across the southern Baie Verte Peninsula toward Hall's Bay.

GEOMORPHOLOGY

The topography of the study area consists of a series of southwest-northeast-trending bedrock ridges, up to 200 m high, separated by the valleys of South Brook, Barney's Brook, West Brook, Burnt Berry Brook and Indian Brook (Figure 1). These brooks flow into Hall's Bay, a major embayment in the northeastern Newfoundland coastline. Both West Brook and South Brook enter lakes two to three kilometres inland from the coast (West Pond and South Pond). The southern Baie Verte Peninsula forms the northern boundary of the sheet, and the southern boundary is marked by the Topsails, reaching altitudes of 300 m in the southwestern corner.

The map area shows a geomorphological zonation from southwest to northeast. The southwestern part of the map sheet is dominated by a thick drift cover having a variety of geomorphological expressions. The most common landform is irregular hummocks up to 20 m high, and 50 to 150 m in diameter, which occur in wide areas of lowland between bedrock ridges. Resistant bedrock knobs in this area are common, and form rôches moutonnée and crag-and-tail landforms. In valley bottoms, a type of ribbed moraine is found, formed by alignment of hummocks perpendicular to the valley and presumably transverse to ice flow.

The central part of the map sheet shows inter-valley ridges dominated by rôches moutonnée, and featureless morainic plains. Valley sides are scarred by numerous meltwater channels, particularly noticeable in the upper West Brook valley, around Indian Pond, and in the valley of Barney's Brook. These channels range from 10 to 150 m wide, 3 to 20 m deep, and are up to 4 km long. The valley bottoms are filled with gravels, having distinct fluvial terraces along Barney's Brook and West Brook.

The northeastern part of the map sheet is dominated by marine sedimentation and numerous deltas and marine terraces (see Scott and Liverman, *this volume*).

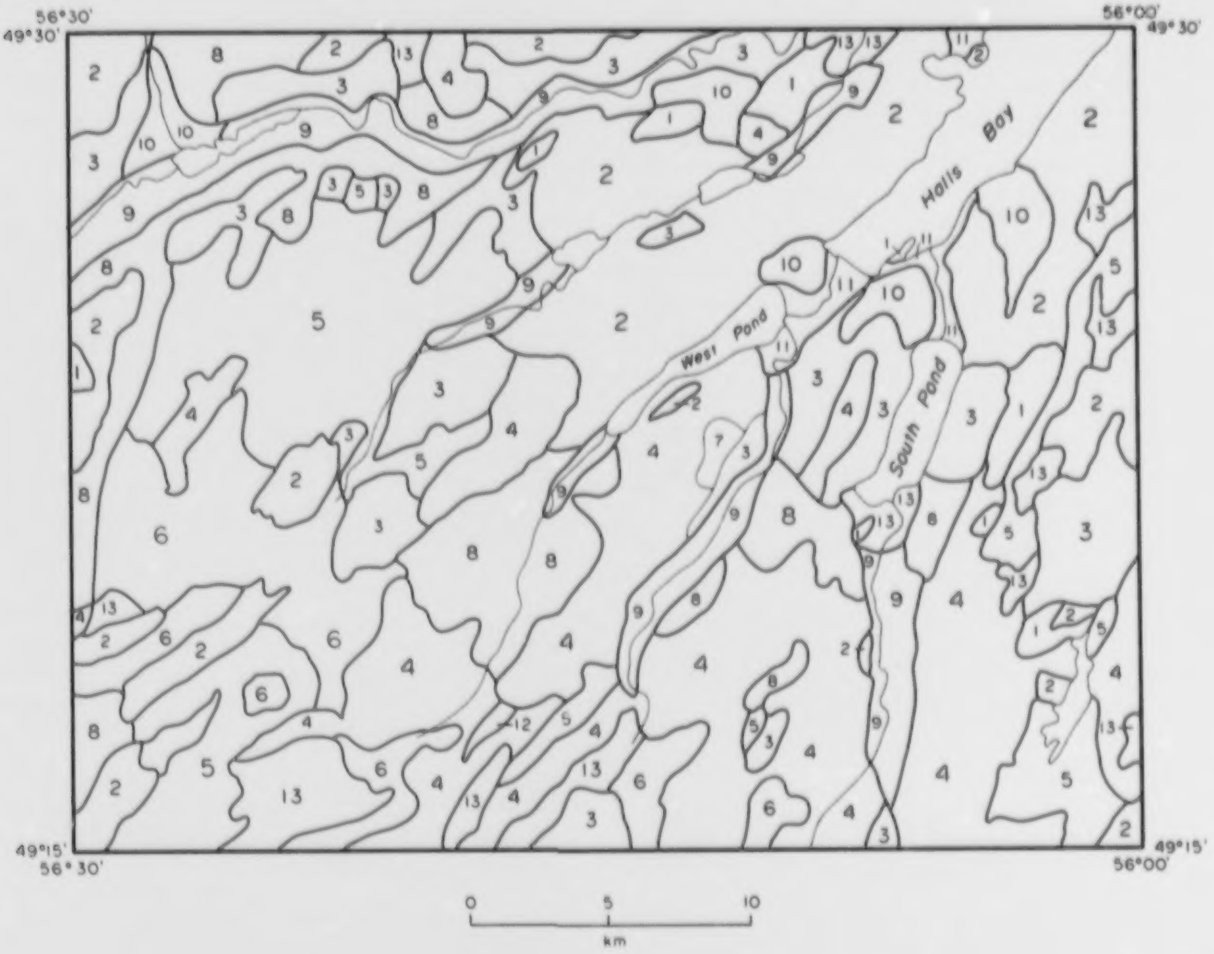
SURFICIAL SEDIMENT

Sediment cover over the area is variable (Figure 4). The coastal areas in the north and northeast have comparatively little surficial sediment cover over high areas; bedrock is intermittently exposed. However, the valleys have a thick surficial fill, related to marine incursion following deglaciation (Scott and Liverman, *this volume*) and deposition of outwash gravels. Large gravel bodies up to 75 m thick were deposited as ice-contact deltas at the mouths of the South Brook, West Brook, Burnt Berry Brook and Indian Brook valleys. Close to the coast, outwash and marine gravels are underlain by well-sorted marine clay and silt, up to 30 m thick (Scott and Liverman, *this volume*). Subsequent fluvial activity resulted in deposition of alluvial gravel, sand, and silt.

The centre and south parts of the study area have a thick surficial cover in low-lying areas, composed mainly of diamicton. Areas of exposed and vegetated bedrock are common on highs, and valley bottoms contain outwash gravel and alluvium. Topography is dominantly hummocky or ridged and areas between hummocks are commonly filled with bog. The eroded till unit is widespread on valley sides where common meltwater channels result in erosion of the diamicton surface, winnowing of fines, and concentration of cobbles and boulders as a lag in channel bottoms. Areas lying between channels consist of relatively undisturbed diamicton.

SEDIMENTOLOGY AND STRATIGRAPHY

Sedimentological work was largely confined to diamictons (described here), and marine sediments (see Scott and Liverman, *this volume*). The sedimentology of diamictons is of interest as the genesis of such sediments is difficult to determine without detailed examination, and the genesis has direct application to drift-prospecting studies.



LEGEND

1	Exposed bedrock: *exposed bedrock with little or no sediment or vegetation cover*
2	Concealed bedrock: *bedrock, mainly concealed by vegetation*
3	Till veneer: *thin (<1.5 m) discontinuous sheet of diamicton overlying bedrock*
4	Till blanket: *continuous diamicton cover having a smooth surface topography between 1.5 and 15 m thick*
5	Hummocky till: *a blanket of diamicton or sand and gravel, 1.5 to 15 m thick, having irregular hummocky topography*
6	Ridged till: *a blanket of diamicton having a topography consisting of irregular ridges transverse to valley axes*
7	Drumlinoid till: *diamicton having a topography consisting of streamlined elongate ridges*
8	Eroded till: *diamicton blanket having surface dissected by meltwater channels containing sand and gravel*
9	Glaciofluvial outwash: *consisting of gravel and sand*
10	Glaciofluvial deltas: *consisting of gravel and sand*
11	Marine sand and gravel: *moderately to well-sorted gravel and sand, found in marine terraces*
12	Alluvium: *Low-relief plains consisting of moderate to well-sorted gravel, sand, silt and clay*
13	Bog: *accumulations of degraded organic matter deposited in poorly drained low-lying areas*

Figure 4. *Surficial geology map, Springdale map area.*

Grain-Size Distribution

The grain-size distribution of diamictons in the area is variable, having a pebble and cobble component estimated to range from 30 to 70 percent. Figure 5 plots preliminary results for matrix texture of diamictons throughout the field area. The diamicton matrix composition averages approximately 38 percent granules, 44 percent sand, and 17 percent silt and clay.

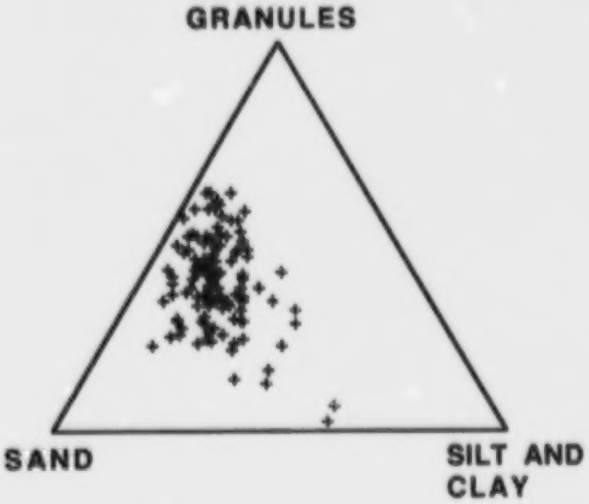


Figure 5. *Ternary diagram from sieve analyses of diamictons*

Clast Fabrics

Sixty-seven clast fabrics were obtained on diamictons throughout the area. Clast fabrics were analyzed on a Macintosh microcomputer using the Stereo™ program (MacEachren, 1989). Clast fabric is an important indicator of the environment of deposition in diamictons, as orientation of clasts is controlled by the processes depositing the diamicton. In lodgment till, strong orientations paralleling and transverse to glacial-flow direction are expected (Lawson, 1979, 1982; Dowdeswell and Sharp, 1986). In basal melt-out till, fabrics are also strong, but may be subsequently modified by reworking. Subaerial debris flow results in less well-oriented inconsistent fabrics, sometimes oriented parallel to local slope (Boulton, 1971; Lawson, 1979).

Clast fabrics must be evaluated using appropriate statistical techniques. Mean orientation, and strength of alignment were calculated by the eigenvector methods of Mark (1973, 1974) and Woodcock (1977). The S1 value measures the strength of the mean clast alignment, and ranges from 0.33 (weak) to 1.0 (strong). Figure 6 is a plot following the method of Woodcock (1977) and Rappol (1985). In this diagram, fabrics plotting in the upper left side of the diagram are considered to have a cluster distribution, whereas those in the lower right part have a girdle distribution. The parallel diagonal lines mark increasing values of a strength parameter (k), with weak fabrics plotting closer to the origin.

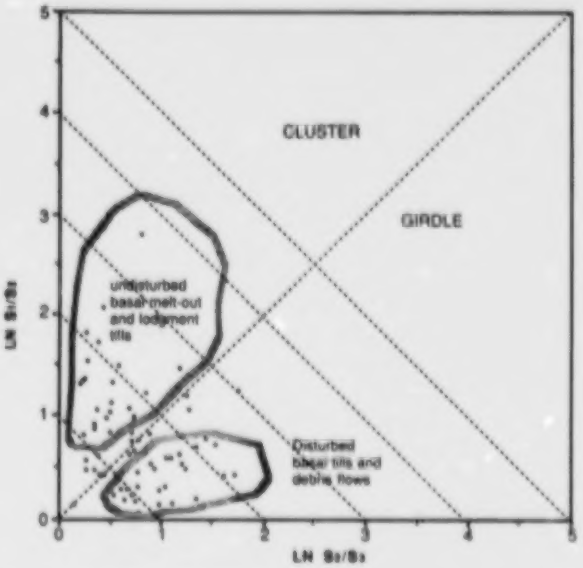


Figure 6. *Diagram of clast fabric eigenvalues, using the method of Woodcock (1977). The Y axis is the natural logarithm of the ratio between S1 and S2, and the X axis the natural logarithm of the ratio between S1 and S3.*

Examination of the diagram shows that fabrics are very variable. About one third of the fabrics plot in the area that Rappol (1985) indicated as being typical of debris flow, one third in the area indicative of undisturbed basal till deposition and the remaining one third in the intervening area. Clast fabrics also show some very local variability, with, in some cases, fabrics from different areas of the same exposure showing different distributions. In such cases, however, it is usually found that one of the fabrics clearly indicates basal deposition, or debris flow; the other plots in the indeterminate region of the diagram.

Fabrics indicative of undisturbed basal tills were obtained sporadically from most areas sampled but are concentrated in two areas. The area northeast of Chain Lakes (Figure 1) is marked by irregular ridges transverse to the valley. Strong clast fabrics are obtained parallel to these ridges, and hence, transverse to ice flow. This suggests that these ridges were deposited by the action of active ice, rather than by stagnation processes. Similar ridges were described by Proudfoot *et al.* (1990), but clast fabrics in these examples were perpendicular to ridge axes. Cowan (1968) described till fabrics from ribbed moraine in Labrador and found that curved ridges showed ridge-parallel fabrics on their limbs. He suggests a subglacial origin for such landforms. The precise mechanism of formation of these ridges is unclear but is probably related to over-ride and shear of either debris-loaded ice, or deposited sediment.

The second area of fabrics indicating basal deposition lies between the Trans-Canada Highway and Rocky Pond (Figure 1). Sediments in this area are discussed in more detail below.

Sedimentary Structures

Diamictons in the area are dominantly massive, but in good exposures, interbeds, and lenses of silt, sand, and gravel are commonly found. Such structures are unlikely to be preserved in lodgment till, and suggest deposition as basal melt-out till, with lenses and beds produced by meltwater flowing in debris-poor areas of basal ice (Shaw, 1982; Haldorsen and Shaw, 1982). A poorly developed horizontal fissility is common in diamictons throughout the map area.

Rarely, more complex sequences are found, having interbedding of sand, gravel and diamicton. Site 152 (Figure 1), for example, shows interbedded diamicton, gravel, sand and silt (Plate 2). Bedding mainly dips to the north, but is deformed and disrupted. Diamicton beds contain some laminated silt intraclasts and compose 50 to 60 percent of the exposure. These interbeds have a similar colour and grain size to diamicton seen elsewhere in the area but have a higher proportion of fines. The abundant sorted sediment in this section indicates that current flow was important in the deposition of the sediment, and the laminated silt and clay suggest standing water. A likely environment of deposition for this sequence is supraglacial melt-out, having debris flow of diamicton, ephemeral ponds, and stream flow (Eyles, 1979). Similar sediments are found at site 156 (Figure 1) and elsewhere in the area.

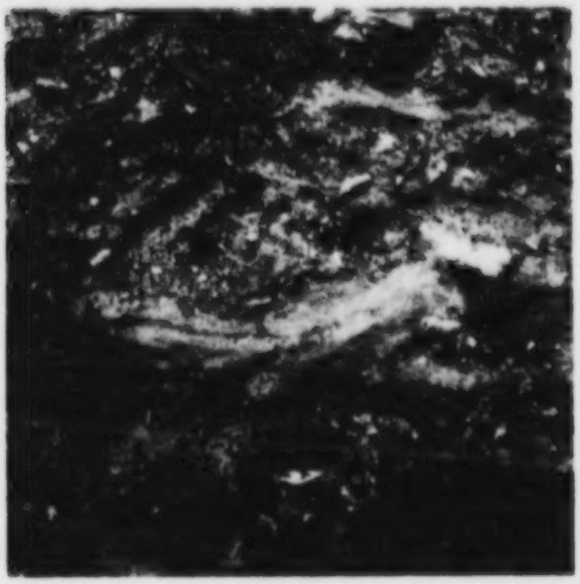


Plate 2. *Sedimentary structures in diamicton, site 152.*

Clast Lithology

Clast lithology of diamictons is diverse, but is dominantly of local origin. No rock type in the area is sufficiently distinctive for use as an indicator lithology, so only gross trends are examined. Figure 7 plots the percentage of granite found in pebble samples from diamictons over the map area. Comparison of the clast composition of pebble samples with outcrop of granitic rocks shows a close relation with the ice-flow history outlined above. Generally high proportions of granitic clasts are found overlying granitic bedrock, but some anomalies exist. High concentrations of granite are found up to 5 km east of the contact between the Topsails Granite and the Springdale Group, mapped by Dean (1977). It is possible that the exact position of this contact may be incorrectly inferred to the west of its actual position, as there is little bedrock exposure in this area. Alternatively, the clast lithology may be explained by dispersal by the eastward to northeastward ice flow in this area. These samples were obtained from hand-dug pits or small sections from an area mapped as hummocky moraine. The surface of such areas is likely composed of supraglacial melt-out till, which should contain high volumes of non-local material. Other anomalies may be explained, in part, by hand-dug pits not penetrating this surface supraglacial veneer (Plate 3).

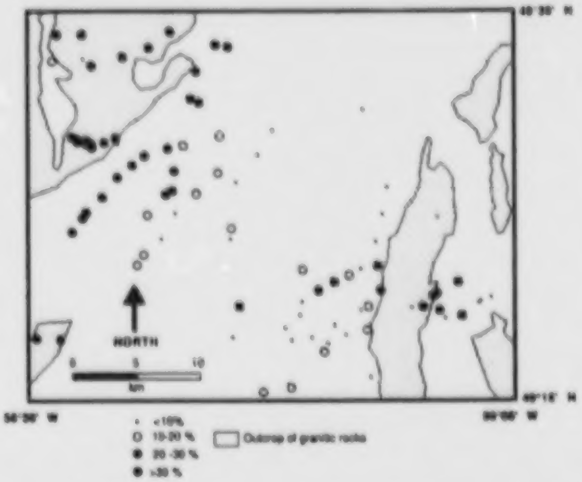


Figure 7. *Proportion of granitic clasts in pebble samples from diamictons; sample size ranges between 80 and 140.*

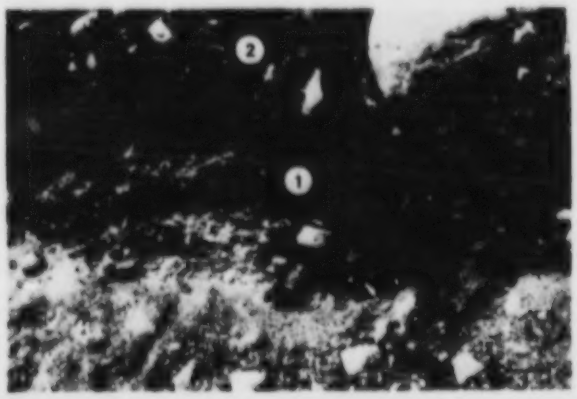


Plate 3. *Common stratigraphy in the south of the map area. A diamicton having clasts of mostly pebbles and granules, (1) is overlain by a cobble and boulder-rich veneer of sandy diamicton (2); section is 1.5 m high.*

STRATIGRAPHY

Multiple diamicton units are commonly interpreted as being deposited by discrete ice-flow events. In such cases, ice-flow direction and sediment provenance may differ for each unit, and thus, identification of such sequences is important in interpreting the results of drift prospecting surveys. A number of sections showed more than a single diamicton unit, and these are discussed in detail below.

Sections South of Indian Pond

Alley (1976) and Alley and Slatt (1975) reported a consistent two-till stratigraphy along the old Trans-Newfoundland highway, in the area east of Sheffield Lake and south of Indian Pond (Figure 1). This area is of particular interest as numerous mineralized floats of unknown origin are found on the surface. Six back-hoe pits were dug to re-examine this stratigraphy. The pits were spaced over 3 km along the old highway, and reached an average of 3 m below ground level (Figure 8). The pit at site 241 exposed mainly gravels, interpreted as glaciofluvial outwash. The other pits exposed diamicton units of varying properties and colour.

The most complex stratigraphy was found at site 242, where three diamicton units are overlain by well-sorted pebble gravel (Figure 8). The three diamicton units are of similar colour. The lowest unit has a Munsell colour of 7.5 YR 5/4 (brown) when moist and 10YR 6/2 (light brownish grey) when dry; the overlying diamicton is 10YR 5/3 (brown) when moist and 10YR 7/3 (very pale brown) when dry; the upper diamicton is 10YR 5/2 (greyish brown) when moist and 10YR 7/3 (very pale brown) when dry.

The lowest is distinguished by a high clast content, and numerous irregular sand and granule lenses. Overlying this is a diamicton having a lower clast content and numerous biconvex gravel lenses that are separated from the underlying diamicton by a bed of granule gravel. The uppermost diamicton is massive, and overlies a gradational contact. The upper contact with the gravel unit is very irregular. Clast lithology of all three diamictons is similar, with about one third granites, and two thirds locally derived andesites. Mineralized floats occur sporadically throughout, but are more common in the upper diamicton. Clast fabrics (Figure 9) are weakly to moderately oriented, decreasing in strength-up section. The lower two diamictons show a mean northward, and the upper a southeastward, clast orientation. The consistency of the lower two fabrics, and their moderate strength suggest that the clast orientation may reflect ice flow at the time of deposition.

The other sections show a diamicton of similar character to that seen at site 242, having weak to moderate fabrics, and variable mean clast orientations with the exception of site 244, which shows two diamicton units. The lower unit has a similar colour to the diamicton seen at site 242, but the upper is a distinctive reddish brown (10YR 5/8, dry; 10YR 6/6, wet). The clast lithology of the upper unit is dominated by volcanics, whereas clasts in the lower diamicton are mostly plutonic igneous rocks. Similar matrix colouration is seen in site 243, where weathered areas around float are a strong brown (7.5 YR 5/8, dry).

Examination of aerial photographs shows that the geomorphology of the area consists of irregular hummocks having a relief of 2 to 5 m, and a diameter of 50 to 100 m. Such topography is considered to be typical of the ice-stagnation environment (Gravenor and Kupsch, 1959). In such settings, ice melts in place during deglaciation, and the sediment held in the ice is deposited by basal and supraglacial melt-out. Considerable resedimentation of deposited diamictons occurs through debris flow as the buried ice melts. Probable sequences in these areas consists of supraglacial melt-out till, in part resedimented, overlying basal melt-out till, also possibly resedimented. The stratigraphy described in this study is compatible with the ice stagnation environment. The weak to moderate fabrics, which have inconsistent trends, are typical of debris flows (Lawson, 1979). The occurrence of sand and granule beds and lenses in the diamictons suggests that water flow was important in their deposition and thus, suggests that melt-out was the primary process.

Alley and Slatt (1975) describe the diamicton stratigraphy in the area as consisting of a 'lower red till' overlain by an 'upper grey till'; both are interpreted as being deposited by lodgement. Alley and Slatt (1975) and Alley (1976) differentiate the two till units by stating that the 'lower red till' is compact, fissile, possesses a strong northeast oriented clast fabric, and contains dominantly angular clasts of local derivation. The 'upper grey till', which is 'somewhat friable' and non-fissile, shows a strong northeast clast orientation at depths of 2 to 3 m, and a strong north to northwest orientation at depths of 1 m; and contains mostly sub-rounded clasts of a mixture of local and distal provenance. Alley and Slatt (1976) state that the presence of angular blocks of the 'lower red till' within a matrix of 'upper grey till' is diagnostic evidence of the lodgment origin of the upper till, and of two distinct ice advances in the area. Further, they conclude on the basis of ice-flow direction deduced from fabric measurements in the 'lower red till' and the shape of the dispersion fan, that the likely source of float is local, and situated close to the southern limit of float discoveries (Figure 8).

It is hard to reconcile the descriptions of Alley and Slatt (1975) with those made in this study. The 'lower red till' may be identified with the upper unit at site 244 and the 'upper grey till' is the diamicton seen elsewhere. Site 244 is located in the area mapped by Alley and Slatt (1975) as showing outcrop of the 'lower red till' at the surface. If the material seen at the surface at site 244 is the 'lower red till' then the presence of a diamicton resembling the 'upper grey till' below it is puzzling. The fabrics obtained from this area show S1 values from 0.46 to 0.60 (weak to moderately oriented) in contrast to the 'strong' fabrics reported by Alley and Slatt (1975) [without the benefit of statistical analysis]. Mean orientation varies from northeast to northwest, but the consistent stratigraphic trends described by Alley and Slatt (1975) were not found. It is possible the few backhoe pits dug

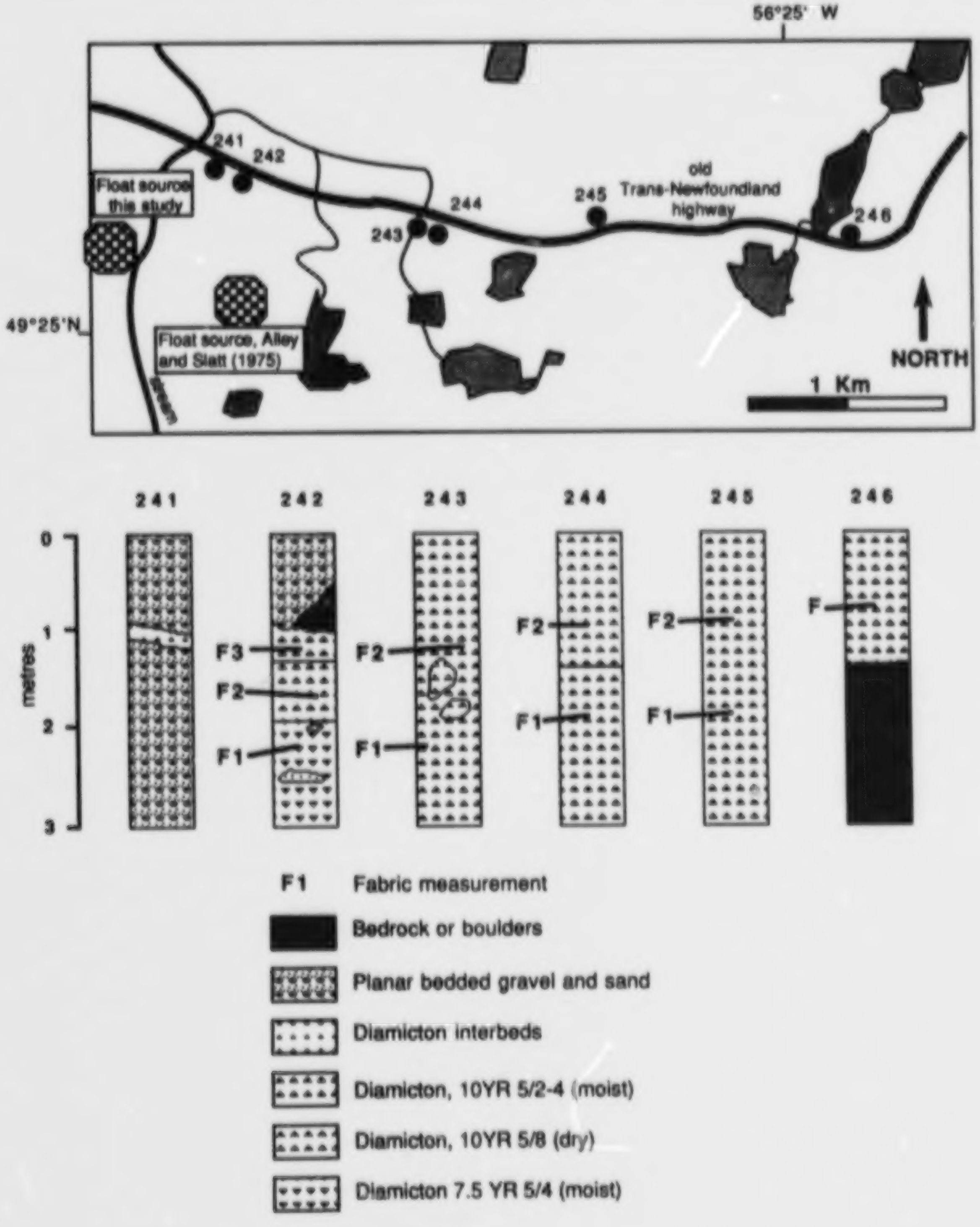
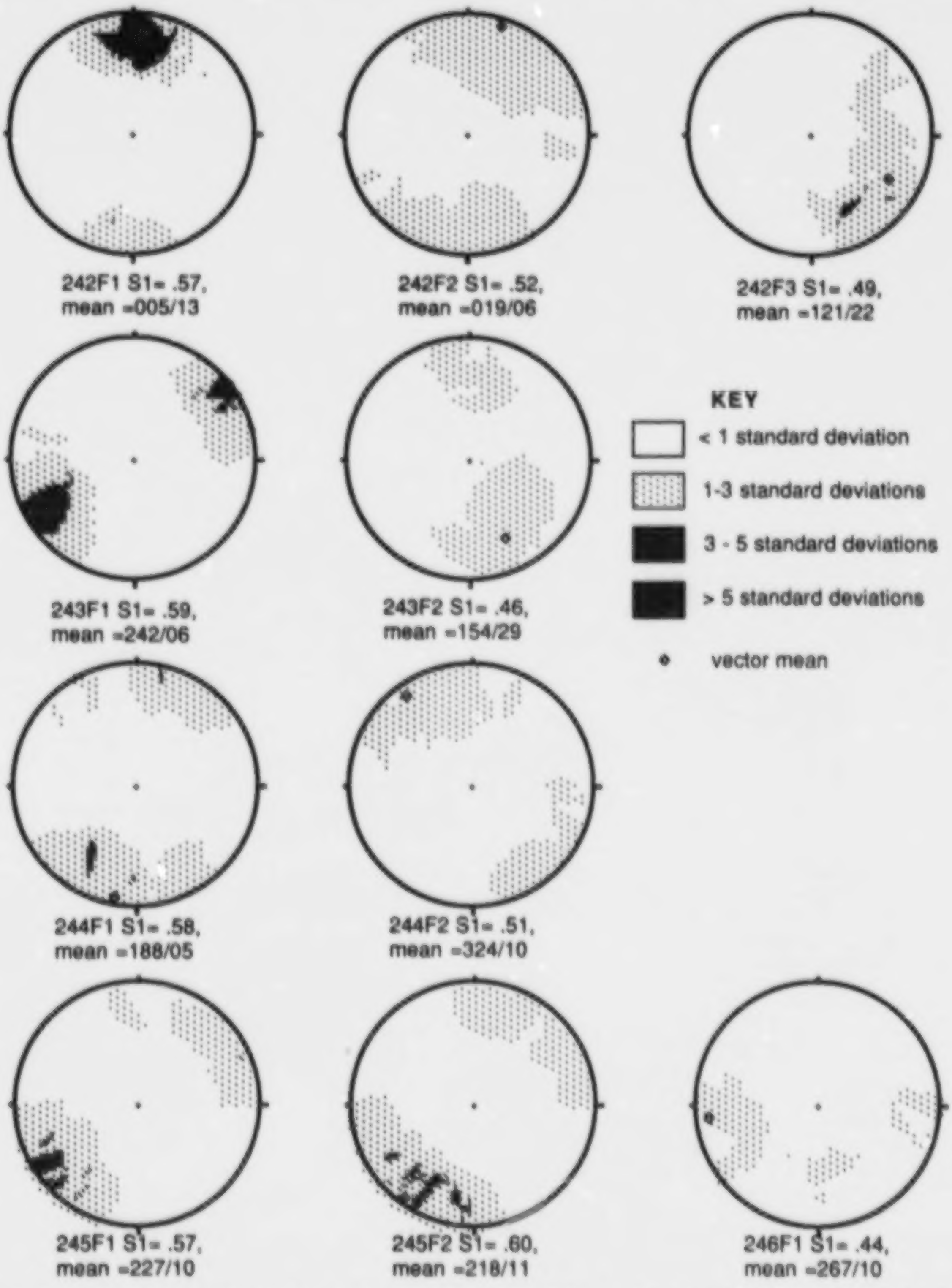

56°25' W
49°25'N
241
242
243
244
245
246
Float source this study
Float source, Alley and Slatt (1975)
old Trans-Newfoundland highway
stream
NORTH
1 Km
0
1
2
3
metres
F1
F2
F3
F
F1 Fabric measurement
Bedrock or boulders
Planar bedded gravel and sand
Diamicton interbeds
Diamicton, 10YR 5/2-4 (moist)
Diamicton, 10YR 5/8 (dry)
Diamicton 7.5 YR 5/4 (moist)

Figure 8. *Map of backhoe pits in the 'main float area' of Alley and Slatt (1975).*



242F1 S1= .57, mean =005/13

242F2 S1= .52, mean =019/06

242F3 S1= .49, mean =121/22

243F1 S1= .59, mean =242/06

243F2 S1= .46, mean =154/29

244F1 S1= .58, mean =188/05

244F2 S1= .51, mean =324/10

245F1 S1= .57, mean =227/10

245F2 S1= .60, mean =218/11

246F1 S1= .44, mean =267/10

Figure 9. *Clast fabrics from backhoe pits in the 'main float area' of Alley and Slatt (1975). S1 is the normalized principal eigenvalue, and the direction of dip and dip of the mean orientation is given as direction/dip. Contours are in standard deviations from the mean following the method of Kamb (1959).*

did not intersect the full stratigraphy described by them from more extensive trenching. The surface till over most of the area is, however, not a lodgment till, and the sections examined can be interpreted as showing deposition from a single advance and the surface material being of supraglacial origin.

The results of this study suggest that the work of Alley and Slatt (1975) should be re-evaluated. An alternative model of ice flow, based on regional striation trends and dispersal of granite clasts in the area east of the float zone (Figure 7), suggests a west-south-westward to east-north-eastward flow. The glaciofluvial gravels found in site 241 formed in a meltwater channel that truncates the dispersal fan on its westerly margin. Thus, an alternative source for the float may be adjacent to, or west of, this channel (Figure 8).

Site 207

This site (Figure 1) consists of an excellent exposure in a borrow pit that shows three distinct diamicton units (Figure 10 and Plate 4). The lowest has moderate to low compaction, about 40 percent pebbles and cobbles, and a moderately to poorly oriented northeast-southwest clast fabric. Sorted sand and silt laminae are common and impart a horizontal fissility to the unit. Overlying a sharp contact, the middle diamicton unit has a higher clast percentage (70 percent), is highly compacted, massive, and shows a strong north-south oriented clast fabric. The clast lithology of the lower two units is similar, dominated by mafic volcanic rock types (of local provenance), and containing about 20 percent granites. The uppermost diamicton unit is variable in thickness, contains many cobbles and boulders, and overlies a sharp undulating basal contact. The matrix is mostly poorly sorted, medium to coarse sand. The clast lithology of this unit is mixed, but it contains a high proportion of rounded granites (70 percent).

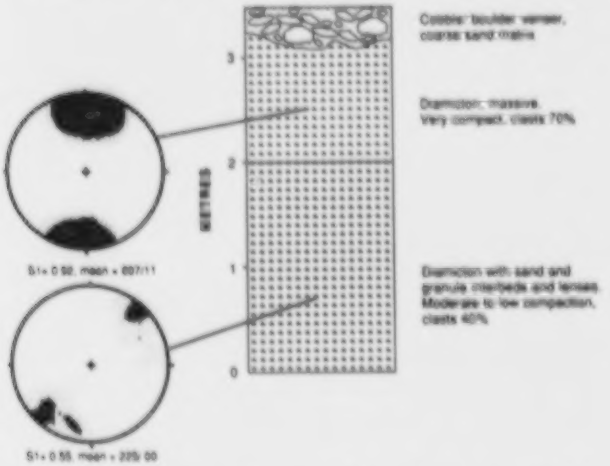

Cobble/ boulder veneer, coarse sand matrix
Diamicton, massive. Very compact, clasts 70%
Diamicton with sand and granule interbeds and lenses. Moderate to low compaction, clasts 40%
METRES
3
2
1
0
S1= 0.92, mean = 007/11
S1= 0.55, mean = 225/00

Figure 10. *Stratigraphy, site 207. See Figure 9 caption for explanation of fabric diagrams.*

This sequence of three units is interpreted as showing a basal melt-out till, overlain successively by a lodgment till, and a supraglacial melt-out till. A basal melt-out genesis for the lowest unit is suggested by the moderate clast fabric, the relatively low compaction, and the common sand laminae (Haldorsen and Shaw, 1982; Lawson, 1979; Shaw, 1987). The high compaction and strong clast fabric of the overlying unit is typical of lodgment tills (Dowdeswell and Sharp, 1986; Kruger, 1979; Lawson, 1979). The uppermost diamicton is thought to be of supraglacial origin due to the volume of coarser material, the numerous non-local clasts, and the coarse grain-size of the matrix (Eyles, 1979; Levson and Rutter, 1986). Thus, this stratigraphy indicates two distinct flow events. The clast fabrics suggest that an earlier northeastward flow deposited a basal melt-out till, which was over-ridden by a later northward flow, which deposited a lodgment till. Upon stagnation of this ice, supraglacial melt-out till was deposited at the surface.

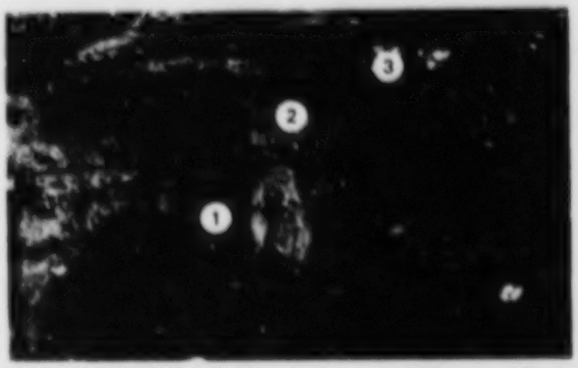


Plate 4. *Multiple diamicton section, site 207, west of Rocky Pond (see text for description; 1 being the lowest unit).*

This sequence is not seen in exposures 1 to 2 km away, where, generally, a sequence of a moderately compact diamicton, which contains some sand and silt laminae overlain by a cobble and boulder veneer, is found. Clast fabrics are variable, having indications of both northwestward and northward flow. These sequences are interpreted as showing deposition of supraglacial melt-out over basal melt-out till, having no evidence of lodgment. Striae in the area indicate a two-phase ice flow, having an early north to northeastward flow and a subsequent northwestward flow. Thus, the lower diamicton at site 207 was probably deposited by basal melt-out following the initial northeastward flow. Re-advance resulted in patchy deposition of lodgment till during a dominantly north to northeastward advance. Where lodgment till was not deposited, it is possible that melt-out tills of the early advance and re-advance cannot be distinguished. Such tills would be of similar character and provenance, and could clearly be separated only by intervening sediments. As the ice retreated, ice flow was dominantly to the northwest (as indicated by striae), and stagnation resulted in deposition of basal melt-out till overlain by a supraglacial melt-out veneer.

Baie Verte Junction Section

This section is exposed in a gravel pit adjacent to the Dorset Trail, 2 km north of its junction with the Trans-Canada

Highway (Figure 1). Recent clearing has exposed three units (Figure 11). The lowest is a diamicton, up to 1.8 m thick, moderately compact, reddish brown (5YR 4/4, moist), having many discontinuous sand and granule beds. Clast fabric is weak, and clast lithology is mixed. Red sandstones and conglomerate clasts are common. The likely source of these clasts is the local Carboniferous clastic rocks mapped by Dean (1977).

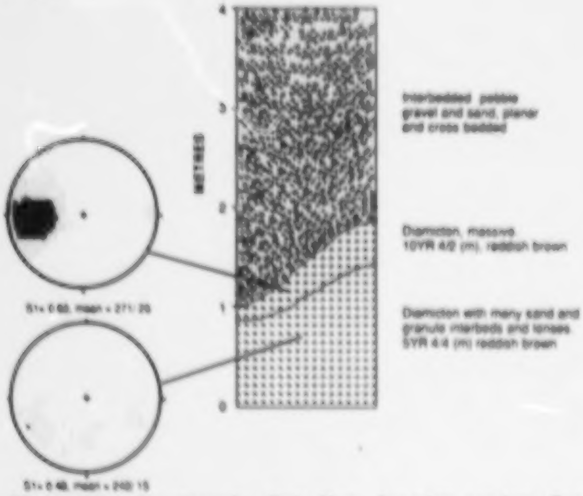

4
3
2
1
0
METRES
Interbedded pebble gravel and sand, planar and cross bedded
Diamicton, massive 10YR 4/2 (m), reddish brown
Diamicton with many sand and granule interbeds and lenses 5YR 4/4 (m) reddish brown
S1= 0.60, mean = 271/20
S1= 0.46, mean = 240/15

Figure 11. *Stratigraphy, Baie Verte Junction section. See Figure 9 caption for explanation of fabric diagrams.*

The middle unit is a diamicton separated from the lower unit by a sharp undulating contact. The contact has up to 0.5 m relief and in section forms a steep-sided trough. This diamicton is up to 0.4 m thick, and follows the slope of the underlying contact. It is dark greyish brown (10YR 4/2, moist), moderately compact, massive and contains many weathered mafic and ultramafic clasts. Granodiorite clasts are also common. Clasts are well-oriented east-west, parallel to the dip of the bed from which the fabric was measured. The uppermost unit consists of interbedded moderately sorted, pebble gravel and sand. The lower beds are contorted, and follow the contours of the underlying unit, but flatten-up section to lie close to horizontal (Figure 11).

The sequence is interpreted as showing diamictons deposited by two phases of ice flow, overlain by ice-contact outwash gravels. The poor clast fabric and interbedded sorted sediments suggest that the lowest unit is not a primary till. It may be a basal melt-out till that has undergone post-depositional resedimentation, or may have been deposited as a debris flow in ice-marginal positions. The contortion of the gravel unit suggests that the trough geometry of the lower contacts formed post-depositionally, probably as buried ice melted. The clast fabric of the upper diamicton is aligned parallel to the dip of the contact, and may have formed through debris flow of material following primary deposition. The upper diamicton contains fewer sandstone clasts of local provenance and the clast assemblage suggests a north to northwestern source for the sediment. Ultramafic rocks and gabbros in this area are only found north of the Green Bay fault (Hibbard, 1983). To deposit these rock types, ice must have moved south from the southern Baie Verte Peninsula into the Indian Brook valley, as suggested by Liverman and St. Croix (1989b). The lower diamicton has a similar clast assemblage to diamictons sampled south of the Indian Brook valley. Although it would be unwise to formulate major conclusions based on two small clast lithology samples, it is speculated that this area was initially glaciated by a northward ice flow (as suggested by ice-flow indicators south of the area). Following retreat of this ice sheet, ice flowed southward or southeastward into the Indian Brook Valley from the Baie Verte Peninsula. A similar ice-flow history was suggested for the King's Point map area by Liverman and Scott (1990) on the basis of striation mapping.

PERIGLACIAL STRUCTURES

A complex deformed sequence of sand and gravel is exposed in a small roadcut section on the north side of the Indian Brook valley. The main feature of this deformation is disruption of planar bedded, well-sorted, medium-grained sand by wedge-shaped units of poorly sorted coarse sand having some granules and pebbles (Plate 5). The wedges are 80 to 100 cm long, 40 cm wide at the surface, and narrow to less than 1 cm at the base. They show some internal stratification parallel to the sides of the wedge. The wedge structures are overlain by moderately to poorly sorted pebble gravel.

Plate 5. *Structure interpreted as an ice-wedge cast in sand and gravel, north of the Indian Brook valley.*

These structures are interpreted as resulting from periglacial action. The stratified filling, and its likely derivation from the overlying gravel bed suggest that these are ice-wedge casts, formed by infill of an ice wedge by sediment as it melted (e.g., Washburn, 1973; Eyles, 1977). Structures interpreted as ice-wedge casts exposed in a gravel pit near the Baie Verte Junction (14 km west of this section) were described by Liverman and St. Croix (1989b). These new discoveries confirm their conclusion of the existence of a periglacial climate following deglaciation of the Indian Brook valley.

DISCUSSION

QUATERNARY HISTORY

There is no local or regional evidence for pre-Late Wisconsinan glacial events. Despite the complex ice-flow history, and multiple diamicton sections, it is thought that all glacial events described here were Late Wisconsinan. The record of ice flow preserved is that of glacial retreat, as striae and sediments associated with advance are obliterated by erosion and thus, little can be said regarding the inception of glaciation. As deglaciation commenced, ice flow was from the area of the Topsails toward the coast. When ice retreated to close to the present coast line, topographic influence resulted in flow toward Hall's Bay in coastal areas, which acted as an outlet for most ice in the area. The deglacial chronology in north-central Newfoundland is based on radiocarbon dates from shells collected from marine sediments in coastal regions, and from organic matter in basal lake sediments (Dyck and Fyles, 1963; Lowdon and Blake, 1975; Blake, 1986, 1987, 1988). Shell dates range from 11,000 to 12,000 years BP, whereas basal lake-sediment dates span 11,800 to 10,400 years BP. However, Macpherson (1990) suggested that the basal lake dates were likely anomalously old, due to problems with aquatic photosynthesis. The shell dates have been assumed to date the formation of the large ice-contact deltas at the valley mouths (Tucker, 1974). It is not clear that the sediment from which these fossils were collected was deposited in association with the coastal marine limit deltas. During this study, shells for dating were collected from glaciomarine silt and clay, which is exposed up to 10 km inland from the ice-contact Springdale delta (see Scott and Liverman, *this volume*). If these shells are of equivalent age to those dated, then it is likely that initial deglaciation and coastal delta formation occurred earlier than 11,000 to 12,000 years BP, with the shell material related to a later still-stand or re-advance of ice.

The ice-wedge casts in the Indian Brook valley indicate the existence of a periglacial climate following initial deglaciation of the area. There is also stratigraphic evidence for a re-advance of ice at site 207. These may be related by postulating a period of cooling following the warming that initiated deglaciation. Evidence of a re-advance of ice was provided by MacClintock and Twenhofel (1940) on the Baie Verte Peninsula, who found marine silts lying between two tills. Brookes (1969, 1977) dated a re-advance of piedmont ice in southwestern Newfoundland at younger than 12,600 ± 140 years BP (GSC-2295). Macpherson and Anderson (1985) interpret radiocarbon dates and pollen from lake sediments in Notre Dame Bay as showing that following initial deglaciation at 13,400 years BP, a climatic deterioration occurred between 11,300 and 10,700 years BP. The structures indicating a periglacial climate described in this paper, and by Liverman and St. Croix (1989), lie close to, but below marine limit. Thus, a speculative sequence of deglaciation might be:

1. Climatic amelioration followed by retreat of ice to close to the present coastline, and construction of ice marginal deltas;
2. further retreat resulted in deglaciation of the major valley systems, and marine inundation. Ice remained on topographic highs inland from the modern coast, likely in the Topsails Hills, but also possibly on the southern Baie Verte Peninsula. This ice may have stagnated, and possibly meltwater channels on valley sides were formed at this time. Deposition of glaciomarine sediments commenced in the flooded valley systems;
3. climatic deterioration resulted in readvance of ice, continued deposition of glaciomarine sediments, and formation of ice wedges in the Indian Brook valley. This may be related to the Younger Dryas cooling event recognized around the North Atlantic, and dated at 11,000 to 10,200 years BP (Mott *et al.*, 1986); and
4. climatic warming, resulting in complete deglaciation. Large areas of ice stagnated on higher ground (the areas mapped as hummocky and ridged till on Figure 4), and provided meltwater to the valley bottoms, eroding the valley sides.

This sequence is very speculative at present. It may be tested in part, once the results of radiocarbon dating on shells collected in the Indian Brook valley are available (see Scott and Liverman, *this volume*). If these shells are of the same age as those collected in coastal areas, then it will substantiate the speculation that the marine limit deltas were deposited prior to 11,000 to 12,000 years BP. Scott and Liverman (*this volume*) further discuss sea-level change in this area.

Following complete deglaciation, sea level continued to fall, resulting in the construction of marine terraces. Rivers became established in their modern courses, depositing alluvium, and deltas at the coast. Vegetation rapidly spread eventually resulting in widespread bog development.

IMPLICATIONS FOR DRIFT PROSPECTING

Despite the simple ice-flow history, the problems encountered in the study of Alley and Slatt (1975) and the alternative interpretation discussed above illustrate the difficulty of using drift prospecting techniques in areas of thick drift. Such methods should be successful if used in conjunction with a sound understanding of the glacial geology. In this area, it is essential that the supraglacial boulder veneer is penetrated during soil sampling. The thickness of this veneer on a given property can only be evaluated by test pitting. The common washed areas (eroded till on Figure 4) will have areas where transport is largely by glaciofluvial processes, rather than ice flow, and this should be considered when evaluating results. The existence of multiple diamicton sections, and a relatively complex stratigraphy, indicate that conventional soil-sampling techniques should be augmented with back-hoe pits and consideration of the genesis of the surficial sediment.

ENVIRONMENTAL AND ECONOMIC GEOLOGY

The numerous sand and gravel areas mapped in the main valleys are likely highly permeable, and thus, may form a source of groundwater at depth. Such areas should be avoided in siting waste-disposal sites, as should the raised marine deposits in coastal areas. The low proportion of silt and clay in surface sediment over much of the area mapped as till, also suggests that the till may be porous and permeable, resulting in seepage problems if used as a waste-disposal site. The marine clays found in the lower Indian Brook valley are likely unstable on steep slopes, and may prove problematic if encountered in construction. They also form a source of clay for pottery and brick making (see Vanderveer, 1977). Mapping suggests that large volumes of such material exists. The sand and gravel bodies form a major source of granular aggregate, although further work on quality is required.

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REFERENCES

Alley D.W.
1976: Drift prospecting and glacial geology in the Sheffield Lake–Indian Pond area, north-central Newfoundland. Unpublished M.Sc thesis, Department of Geology, Memorial University, St. John's, Newfoundland, 215 pages.

Alley, D.W. and Slatt, R.M.
1975: Drift prospecting and glacial geology in the Sheffield Lake–Indian Pond area, north-central Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 75-3, 96 pages.

Blake, W. Jr.
1986: Geological Survey of Canada Radiocarbon Dates XXV. Geological Survey of Canada, Paper 85-7, 32 pages.

1987: Geological Survey of Canada Radiocarbon Dates XXVI. Geological Survey of Canada, Paper 86-7, 60 pages.

1988: Geological Survey of Canada Radiocarbon Dates XXVII. Geological Survey of Canada, Paper 87-7, 100 pages.

Bostock, H.H.
1988: Geology and petrochemistry of the Ordovician volcano-plutonic Robert's Arm Group, Notre Dame Bay, Newfoundland. Geological Survey of Canada, Bulletin 369, 84 pages.

Boulton, G.S.
1971: Till genesis and fabric in Svalbard, Spitsbergen. *In* Till: a symposium. *Edited by* R.P. Goldthwait, Ohio State University Press, Columbus, Ohio, pages 41-72.

Brookes, I.A.
1969: Late glacial marine overlap in western Newfoundland. Canadian Journal of Earth Sciences, Volume 6, pages 1397-1404.

1977: Radiocarbon age of Robinson's Head moraine, west Newfoundland, and its significance for postglacial sea level change. Canadian Journal of Earth Sciences, Volume 14, pages 2121-2126.

Cowan W.R.
1968: Ribbed moraine: Till fabric analysis and origin. Canadian Journal of Earth Sciences, Volume 5, pages 1145-1159.

Coyle, M. and Strong, D.F.
1987: Geology of the Springdale Group: a newly recognised Silurian epicontinental-type caldera in Newfoundland. Canadian Journal of Earth Sciences, Volume 24, pages 1135-1148.

Dean, P.L.
1977: A report on the metallogeny of the Notre Dame Bay area, Newfoundland. Department of Mines and Energy, Mineral Development Division, Report 77-10, 17 pages, and accompanying maps.

Dowdeswell, J. and Sharp, M.J.
1986: Characterization of pebble fabrics in modern terrestrial glacigenic sediments. Sedimentology, Volume 33, pages 699-710.

Dyck, W. and Fyles, J.G.
1963: Geological Survey of Canada radiocarbon dates I and II. Geological Survey of Canada, Paper 63-21, 31 pages.

Eyles, N.
1977: Late Wisconsinan glaciotectonic structures and evidence of postglacial permafrost in north-central Newfoundland. Canadian Journal of Earth Sciences, Volume 14, pages 2797-2806.

1979: Facies of supraglacial sedimentation on Icelandic and Alpine temperate glaciers. Canadian Journal of Earth Sciences, Volume 16, pages 1341-1361.

Grant, D.R.
1973: Surficial geology, Springdale. Geological Survey of Canada, Open File Map 180.

1986: Surficial geology, Springdale. Geological Survey of Canada Open File Map 1312.

Gravenor, C.P. and Kupsch, W.O.
1959: Ice disintegration features in western Canada. Journal of Geology, Volume 67, pages 48-64.

Haldorsen, S. and Shaw, J.
1982: Meltout till and the problem of recognising genetic varieties of till. Boreas, Volume 11, pages 261-269.

Hibbard, J.
1983: Geology of the Baie Verte Peninsula, Newfoundland. Newfoundland and Labrador Department of Mines and Energy, Mineral Development Division, Memoir 2, 279 pages.

1989: The Humber and Dunnage Zones of the Baie Verte Peninsula. *In* Geology of Newfoundland and Labrador. *Edited by* J.P. Hodych and A.F. King. Newfoundland Journal of Geological Education, Volume 10, pages 47-54.

Kamb, W.B.
1959: Ice petrofabric observations from Blue Glacier, Washington, in relation to theory and experiments. Journal of Geophysical Research, Volume 64, pages 1891-1919.

Kean, B.F.
1977: Geological compilation of the Newfoundland Central Volcanic Belt. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 7730.

Kruger, J.
1979: Structures and textures in till indicating subglacial deposition. Boreas, Volume 8, pages 323-340.

Lawson, D.E.
1979: A comparison of the pebble orientations in ice and deposits of the Mantanuska Glacier, Alaska. Journal of Geology, Volume 90, pages 78-84.

1982: Mobilisation, movement, and deposition of active sub-aerial sediment flows, Matanuska Glacier, Alaska. Journal of Geology, Volume 90, pages 279-300.

Levson, V. and Rutter, N.W.
1986: A facies approach to the stratigraphic analysis of Late Wisconsinan sediments in the Portal Creek area, Jasper National Park, Alberta. Géographie Physique et Quaternaire, Volume XL, pages 129-144.

Liverman, D.G.E. and St. Croix, L.
1989a: Ice flow indicators on the Baie Verte Peninsula. Department of Mines and Energy, Mineral Development Division, Open File Map 89-36.

1989b: Quaternary geology of the Baie Verte Peninsula. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 237-247.

Liverman, D.G.E. and Scott, S.
1990: Quaternary geology, King's Point map sheet (NTS 12H/9). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 27-38.

Liverman, D.G.E., St. Croix, L., Vatcher, H. and Scott, S.
1990: Ice flow indicators, Springdale map sheet (12H/8). Open file map 12H/8 (1189), Newfoundland Department of Mines and Energy, Geological Survey Branch Map 90-123.

Lowdon, J.A. and Blake, W.
1975: Geological Survey of Canada Radiocarbon Dates XV. Geological Survey of Canada, Paper 75-7, 31 pages.

Lundqvist, J.
1965: Glacial geology in northeastern Newfoundland. Geologiska Foreningen i Stockholm Forhandlingar, Volume 87, pages 285-306.

MacEachran, D.B.
1989: Stereo™, the stereographic projection program for the Macintosh. Distributed by Rockware Inc, Wheat Ridge, Colorado, U.S.A.

MacClintock, P. and Twenhofel, W.H.
1940: Wisconsin glaciation of Newfoundland. Bulletin of the Geological Society of America, Volume 51, pages 1729-1756.

Macpherson, J.B.
1990: The Younger Dryas in Eastern Newfoundland. *In* CANQUA/AMQUA, 1990, Programme and Abstracts, Waterloo, page 24.

Macpherson, J.B. and Anderson, T.W.
1985: Further evidence of late glacial climatic fluctuations from Newfoundland: pollen stratigraphy from a north coast site. *In* Current Research, Part B. Geological Survey of Canada, Paper 85-1, pages 383-390.

Mark, D.M.
1973: Analysis of axial orientation data, including till fabrics. Bulletin of the Geological Society of America, Volume 84, pages 1369-1374.

1974: On the interpretation of till fabrics. Geology, Volume 2, pages 101-104.

Mott, R.J., Grant, D.R., Stea, R.R. and Occhietti, S.
1986: Late glacial climatic oscillation in Atlantic Canada equivalent to the Allerød/Younger Dryas event. Nature, Volume 323, pages 247-250.

O'Donnel, N.D.
1973: Glacial indicator trains near Gullbridge, Newfoundland. Unpublished M.Sc. thesis, Department of Geology, University of Western Ontario, 258 pages.

Proudfoot, D.N., Scott, S. St. Croix, L. and Taylor D.M.
1990: Quaternary geology of the Burnt Hill (NTS 2D/5)–Great Gull Lake (NTS 2D/6) map area in southeast-central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 49-64.

Rappol, M.
1985: Clast-fabric strength in tills and debris flows compared for different environments. Geologie en Mijnbouw, Volume 64, pages 327-332.

Scott, S., Liverman, D.G.E. and St. Croix, L.
1990: Ice-flow indicators on the King's Point map sheet. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File map 12H (1117).

Shaw, J.
1982: Melt-out till in the Edmonton area, Alberta, Canada. Canadian Journal of Earth Sciences, Volume 19, pages 1548-1569.

1987: Glacial sedimentary processes and environmental reconstruction based on lithofacies. Sedimentology, Volume 34, pages 103-116.

St. Croix, L. and Taylor, D.M.
This volume: Ice-flow indicators in the Notre Dame Bay area, Newfoundland.

Swinden, H.S.
1987: Geology and mineral occurrences in the central and northern parts of the Roberts Arm Group, central Newfoundland. *In* Current Research, Part A, Geological Survey of Canada, Paper 87-1A, pages 381-390.

Tucker, C.M.
1973: The glacial geomorphology of west-central Newfoundland; Halls Bay to Topsails. Unpublished M.Sc. thesis, Department of Geography, Memorial University, Newfoundland, 132 pages.

1974: A series of raised Pleistocene deltas in Halls Bay, Newfoundland. Maritime Sediments, Volume 10, pages 1-7.

Vanderveer, D.G.
1977: Clay deposits of Newfoundland and Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-9, 41 pages.

Washburn A.L.
1973: Periglacial Environments and Processes. Edwin Arnold, London, 320 pages.

Woodcock, N.H.
1977: Specification of clast fabric shapes using an eigenvalue method. Bulletin of the Geological Society of America, Volume 88, pages 1231-1236.

*Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 45-59*

GRANULAR AGGREGATE-RESOURCE MAPPING IN CENTRAL AND NORTHEASTERN NEWFOUNDLAND

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ABSTRACT

This report gives preliminary results of 1:50,000-scale granular aggregate-resource mapping in the Botwood, Hodges Hill and Point Leamington map areas of central and northeastern Newfoundland. The objective of the project is to conduct a regional aggregate study to locate suitable deposits to assist the construction industry when development occurs in these areas. The largest known potential deposits are located at Peters River, Browns Arm, Northern Arm Brook, Exploits River, Jumpers Brook, Kite Cove and Southwest Brook.

INTRODUCTION

The second year of a regional aggregate-resource mapping program for the Island of Newfoundland was completed during the 1990 field season. The objectives of the program are to locate, map and sample sand, gravel and glacial till materials. Field sampling concentrated on glaciofluvial outwash deposits, which are the major sources of sand and gravel in the province. These deposits are excellent sources of low silt-clay aggregate, which are necessary for use in concrete, asphalt, and Class A and B road gravels. Glacial till is generally regarded as poor quality aggregate due to its large silt-clay fraction and therefore, was given less attention during field investigations.

MINERAL AGGREGATE–A BRIEF DESCRIPTION

Mineral aggregates are defined as any hard, inert material such as gravel, sand, crushed stone or other mineral material that is used in the construction industry (Carter, 1981). They are used extensively in all types of construction activities related to domestic, industrial or other developments. These materials can be, (a) used in an unprocessed form as pit and run, (b) processed and used as Class A road gravels (Department of Transportation, 1987), (generally, aggregate consisting of 100 percent grain-sizes less than 19 mm in diameter and less than 6 percent silt-clay content plus a specified range of percentages for size fractions between these upper and lower limits) and Class B road gravels (generally, aggregate consisting of 100 percent grain-sizes less than 102 mm in diameter and containing less than 6 percent silt-clay plus a specified range of percentages for size fraction between these upper and lower limits) and (c) mixed with a cementing agent to form concrete, asphalt and mortar. Road construction is one of the major uses of aggregate materials. From a municipal viewpoint, street, water and sewer service, driveway construction and building foundations all require aggregate. Backfill is another major use, as are topsoil-type materials for landscaping.

Not all of the materials are suitable as aggregate. Vanderveer (1983) defined the quality of mineral aggregate by their composition. Aggregates containing too much or too little silt and clay when used in road construction can cause instability, e.g., flowage in the base of too much fine material, or the loss of compaction properties in the case of too little fine material. Also, too much fine material in concrete (> 2 percent) can interfere with the bonding process between the aggregate and the cementing agent. The presence of deleterious substances such as silt-clay coating or iron-oxide staining on the surface of the aggregate, and the presence of certain friable or blade-shape fragments, often cause bonding problems with the cementing agent, or the breakdown of aggregate with time.

Aggregates are a high-volume, low-cost material. The cost of transport represents, on average, 30 percent of the delivered price (Vanderveer, 1982). Thus, the location of resources relatively close to the users is important. In the case of Newfoundland, the many users throughout the Island makes a regional-mapping project of the resources vital.

LOCATION AND ACCESS

The field area consisted of the Botwood (2E/3), Hodges Hill (2E/4) and Point Leamington (2E/6) map areas of central and northeastern Newfoundland (Figures 1 and 2).

Most of the field area is easily accessible, by the many major road-routes throughout the study area, numerous logging roads (in use and abandoned), which are usable by all-terrain-vehicles, and waterways accessible by boat and canoe. The only areas with poor ground access are located in the northern–central part of map area 2E/3, between Burnt

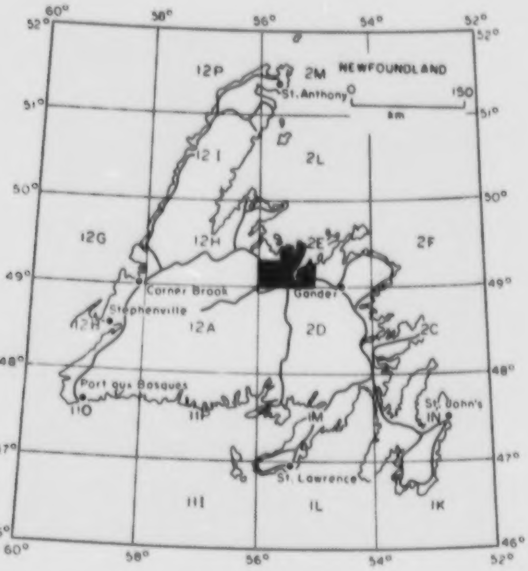

Figure 1. *Location map.*

Arm and Lewisporte, and in the central part of map area 2E/4, between New Bay Pond Road and Mary Ann Lake.

PREVIOUS WORK

Surficial geological mapping at 1:50,000 scale (based mainly on 1978 reconnaissance aerial photographic interpretation) has been completed in most of the study area (Kirby *et al.*, 1989).

An aggregate-resource program was conducted by the Department of Mines and Energy from 1978 to 1982 (Environmental Geology Section, 1983; Kirby *et al.* 1983) covering a 6-km-wide corridor along all major roads and a wider radius around towns and cities in Newfoundland and Labrador. Kirby (personal communication, 1989) conducted detailed sampling in selected granular aggregate deposits in the 2E/3 map area. These deposits are situated along Southwest Brook, Northern Arm, Peters River and the Exploits River. In addition to this data, geotechnical bedrock maps were compiled at a scale of 1:250,000 (Bragg, 1986). Bedrock-aggregate mapping at a scale of 1:50,000 was conducted in central Newfoundland (Bragg, 1990) to locate suitable bedrock deposits where granular aggregates are scarce and/or poor in quality.

GEOLOGICAL SETTING

The bedrock geology of the area consists of intrusive, volcanic and sedimentary rocks (Figure 3). Intrusive rocks dominate the western part of map area 2E/4, the southeast corner of map area 2E/3 and in smaller zones intermixed with volcanic and sedimentary rocks in other parts of the map area.

Intrusive rocks consist essentially of diorite, gabbro, granite, quartz diorite, quartz monzonite and minor trondhjemite. Volcanic and sedimentary rocks include basic to acidic volcanics, sandstone, shale, greywacke, conglomerate and chert.

MAPPING AND ANALYTICAL METHODS

Field work was undertaken in a similar manner to that outlined by Kirby *et al.* (1983). Interpretation of 1:50,000-scale black-and-white aerial photographs was used as a guide to locate potential deposits of sand and gravel. Following this, interpretation of coloured aerial photographs at 1:12,500 scale was conducted in selected areas based on deposit type (e.g., glaciofluvial, marine, till) to delineate deposit boundaries accurately. Where exposures were present, field sampling was carried out at 0.5 to 1.0 km intervals in outwash deposits, and at 1.5 to 2 km intervals in till. Additional samples were taken at each deposit wherever changes in sediment type were observed, where quality differences were apparent, or wherever sediments of variable quality or texture could be quarried separately.

Where possible, samples were taken from natural exposures such as stream cuts, shorelines, and gullied areas or from man-made exposures such as roadcuts and pit and quarry excavations. Where these types of exposures were not available, samples were collected from hand-dug pits, slightly greater than 1 m in depth.

Sampling provided material for petrographic and grain-size analyses, and Los Angeles abrasion and soundness tests. Approximately 15 kg of material were collected for field sieving. Field sieving and petrographic analysis were done on all samples containing >8mm-size material. A split (70 to 140 g) of the sand-silt-clay fraction (<8mm) was retained for laboratory sieving. The laboratory sieving involved drying and splitting the sample to manageable quantities (70 to 140 g) and wet and/or dry sieving of each sample following the procedures outlined in Ricketts (1987). Los Angeles abrasion and soundness tests will be done on selected samples during this coming year. These tests will follow ASTM standards C 88-83, (1990), for soundness, and C 131-89, (1990), for abrasion.

CLAST-TYPE ANALYSIS

The aggregate samples were examined to help determine the petrographic characteristics of the pebble fraction (16 to 32 mm). A petrographic number was calculated using similar procedures outlined in CSA standard A23.2.30 (Canadian Standards Association, 1973). The petrographic number, which can range from 100 to 1000, is derived by taking the sum of the percentage of each rock type present in the pebble fraction (approximately 50 pebbles) multiplied by a petrographic factor (based on soundness and durability) assigned to that rock type (Bragg, *this volume*). The petrographic factor is determined mostly by the rock type and textures present in a given pebble sample and also by the presence of silt-clay coatings, weathering, staining, degree of sphericity, rounding and fractures. The lower the petrographic number, the better the quality of aggregate material. For example, a clean, hard, fresh granite would

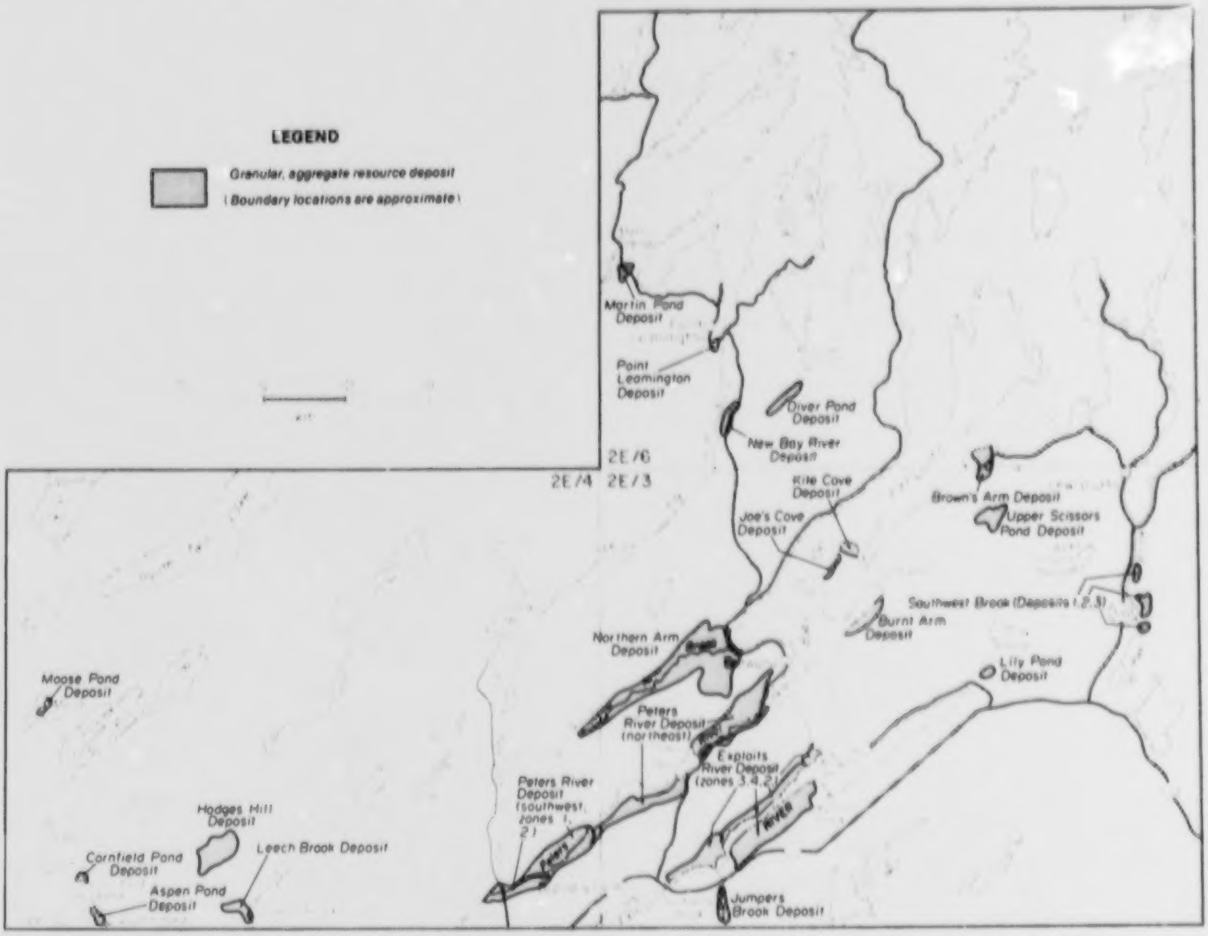
LEGEND
Granular, aggregate resource deposit
(Boundary locations are approximate)
Martin Pond Deposit
Point Leamington Deposit
Diver Pond Deposit
New Bay River Deposit
2E/6
2E/4
2E/3
Kite Cove Deposit
Joe's Cove Deposit
Brown's Arm Deposit
Upper Scissors Pond Deposit
Southwest Brook (Deposits 1,2,3)
Burnt Arm Deposit
Lily Pond Deposit
Northern Arm Deposit
Moose Pond Deposit
Peters River Deposit (northeast)
Exploits River Deposit (zones 3,4,2)
Peters River Deposit (southwest, zones 1, 2)
Hodges Hill Deposit
Leech Brook Deposit
Cornfield Pond Deposit
Aspen Pond Deposit
Jumpers Brook Deposit

Figure 2. *Potential aggregate-resource deposits in the Botwood (2E/3), Hodges Hill (2E/4) and Point Leamington (2E/6) map area.*

normally have a petrographic number of 100, whereas for a friable, soft shale it would be 1000. A combination of different rock types with different petrographic factors in one granular sample would give a petrographic number between 100 and 1000 (Table 1). For most purposes, aggregate material used in concrete, in Newfoundland, requires a petrographic number of 135 or less, and a petrographic number of 150 or less for use in road asphalt and Class A and B gravels (Department of Transportation, 1987).

RESULTS

Grain-size analyses were done on 225 samples. The results plot as cumulative curves for each sample similar to those of Kirby *et al.* (1983). A computer program is used to calculate percentages of gravel, sand, and silt-clay data. Individual sieve percentages can also be calculated from these graphs.

A review of landform classification and grain-size analyses will be made and results drafted on 1:50,000-scale maps. These maps will show aggregate zones determined by quantity and type of material, sample numbers and type of sample collected (sand, gravel, silt and till). Boundaries around designated aggregate zones will be determined principally from airphoto investigations, and may not represent the true extent of any deposit that can be used as a source of aggregate.

POTENTIAL DEPOSITS

The following are brief descriptions (described in order by mapsheet) of some of the potential granular aggregate-resource deposits in the study area (Figure 2; Table 2). The descriptions include deposit location, length, width and thickness of deposits, exposure types where samples were collected, average percentage of gravel, sand, and silt-clay and range of petrographic numbers for each deposit (results of grain-size and petrographic analyses are based on a compilation of sample data collected during the 1990 field season and previous sample programs by the Department of Mines and Energy since 1978).

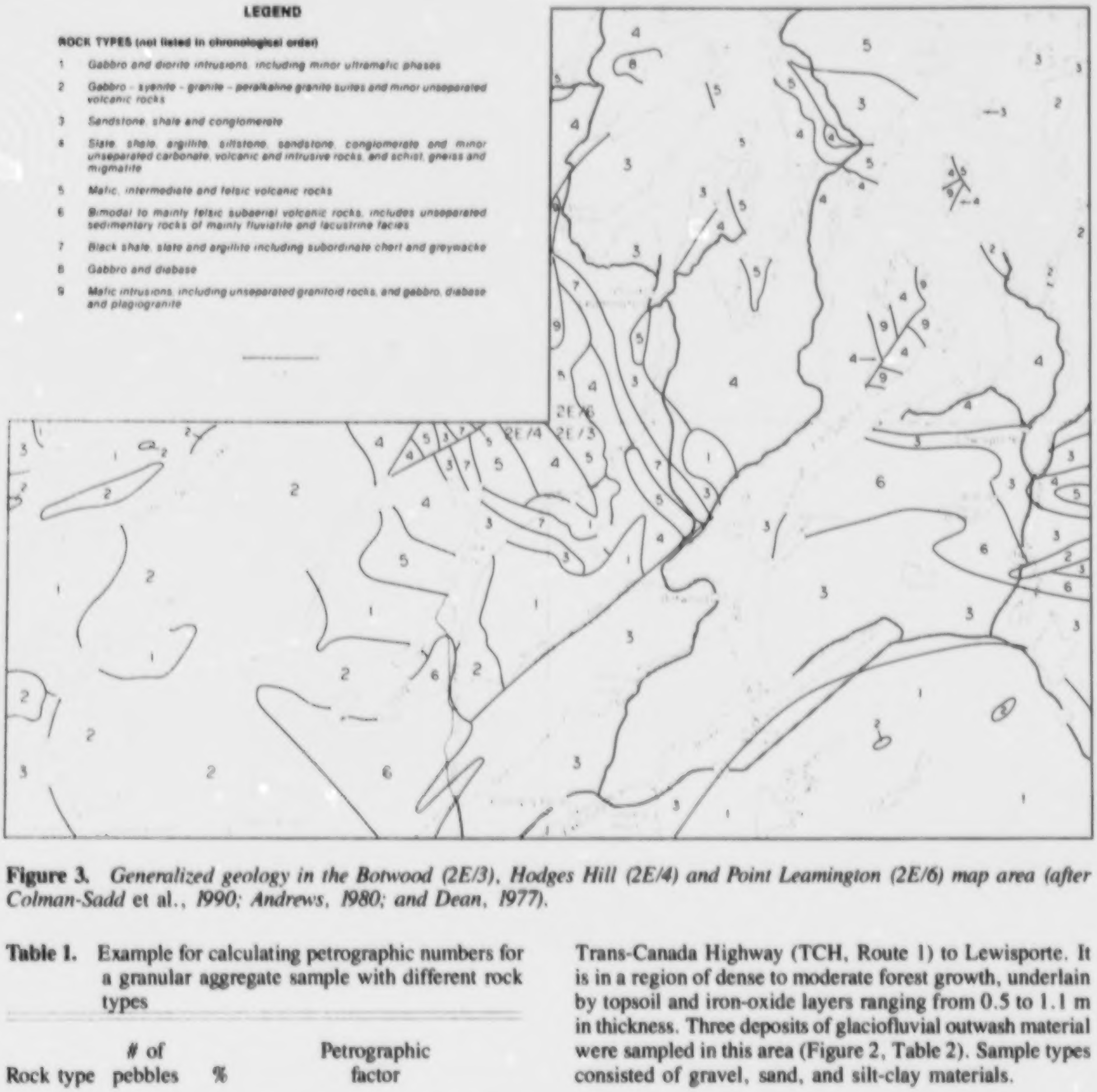
LEGEND
ROCK TYPES (not listed in chronological order)
1 Gabbro and diorite intrusions, including minor ultramafic phases
2 Gabbro - syenite - granite - peralkaline granite suites and minor unseparated volcanic rocks
3 Sandstone, shale and conglomerate
4 Slate, shale, argillite, siltstone, sandstone, conglomerate and minor unseparated carbonate, volcanic and intrusive rocks, and schist, gneiss and migmatite
5 Mafic, intermediate and felsic volcanic rocks
6 Bimodal to mainly felsic subaerial volcanic rocks, includes unseparated sedimentary rocks of mainly fluviatile and lacustrine facies
7 Black shale, slate and argillite including subordinate chert and greywacke
8 Gabbro and diabase
9 Mafic intrusions, including unseparated granitoid rocks, and gabbro, diabase and plagiogranite
2E/4
2E/6
2E/3

Figure 3. *Generalized geology in the Botwood (2E/3), Hodges Hill (2E/4) and Point Leamington (2E/6) map area (after Colman-Sadd* et al., *1990; Andrews, 1980; and Dean, 1977).*

Table 1. Example for calculating petrographic numbers for a granular aggregate sample with different rock types

Rock type	# of pebbles	%		Petrographic factor	
Shale	12	22	x	10	= 220
Granite	27	50	x	1	= 50
Sandstone	10	19	x	3	= 57
Schist	5	9	x	6	= 54
				Sum	= 381
				Petrographic number	= 381

MAP AREA 2E/3

SOUTHWEST BROOK

Southwest Brook is located in the eastern part of map area 2E/3, along the east side of Route 340 leading from the Trans-Canada Highway (TCH, Route 1) to Lewisporte. It is in a region of dense to moderate forest growth, underlain by topsoil and iron-oxide layers ranging from 0.5 to 1.1 m in thickness. Three deposits of glaciofluvial outwash material were sampled in this area (Figure 2, Table 2). Sample types consisted of gravel, sand, and silt-clay materials.

Deposit 1 is situated 2 km south of Lewisporte. This deposit is 900 m long, 200 m wide and up to 8 m thick. Eighteen samples taken from this area were collected from quarries and backhoe pits averaging a depth of 3.4 m. Grain-size analyses of these samples indicate variable textures throughout the deposit (Figure 4), but generally consists of class-B-type material mixed with medium sandy gravel, fine to medium sand, silty sand and silt. Six of the 14 samples analyzed in this area have silt-clay content greater than 4 percent with a high of 38.7 percent. Quarrying in the northern part of this area has resulted in approximately 25 percent removal of this deposit. Remaining aggregate in the northern area consists of less usable silty-sand and silt-clay type material. Areas south of the quarry require further sampling

Table 2. Summary and comparisons of aggregate zones in central and northeastern Newfoundland

		Grain-size analyses				Petrographic analyses		
Deposit	Estimated m3 x10⁶	# of samples analyzed	% Grv. (+5mm)	% Sd. (+.078 to 5mm)	% Slt-Cly (-78 um)	# of samples analyzed	Range	Average
Southwest Br.								
Zone 1	0.1−0.5	18	50.0	43.0	7.0	14	144-389	252
Zone 2	0.5−1.0	6	39.9	57.9	2.2	3	148-293	208
Zone 3	0.5−1.0	2	32.0	66.0	1.4	1	327	327
Lily Pond	< 1	1	1.0	95.7	3.2	0		
Kite Cove	5.0−10	1	56.0	43.7	2.3	1	238	238
Northern Arm	> 10	28	44.6	54.4	1.0	19	119-340	218
Peters River (northeast)	> 10	28	43.0	55.9	1.1	17	151-450	273
Exploits River								
Zone 1	0.5−1.0	3	49.0	50.8	0.2	3	408-482	442
Zone 2	5.0−10	7	7.3	92.6	0.1	0		
Zone 3	5.0−10	14	65.5	34.0	0.5	12	185-704	406
Zone 4	> 10	30	37.3	62.2	0.5	21	140-498	270
Jumpers Brook	0.5−1.0	5	36.2	59.5	4.3	3	176-282	212
Peters River (southeast)								
Zone 1	> 10	3	11.0	80.0	9.0	1	455	455
Zone 2	5.0−10	12	51.8	46.7	1.5	9	146-503	286
Hodges Hill	0.5−1.0	2	61.2	38.6	0.3	2	150-156	153
Aspen Pond	0.1−0.5	1	86.8	13.0	0.2	1	224	224
Cornfield Pond	< 0.1	1	67.9	31.8	0.3	1	106-106	106
Moose Pond	0.1−0.5	3	39.9	54.6	8.5	3	168-202	185
Browns Arm	>10	7	51.4	47.6	0.9	4	213-457	324
Diver Pond	0.1−0.5	2	76.6	23.3	0.1	2	236-248	242
New Bay River	0.1−0.5	3	25.7	73.2	0.1	2	438-517	477
Point Leamington	0.1−0.5	6	46.6	50.5	2.9	4	213-457	324
Martin Pond	0.1−0.5	2	64.4	34.9	0.7	2	152-534	346

Note: Estimated quantities in Table 2 are based on airphoto analysis and field investigation where roadcuts, shallow hand-dug pits and natural exposures permitted. Detailed sampling methods such as drilling were not conducted. Grain-size percentages are based on a compilation of samples for each deposit and do not take into account extent and thickness of units at any one location.

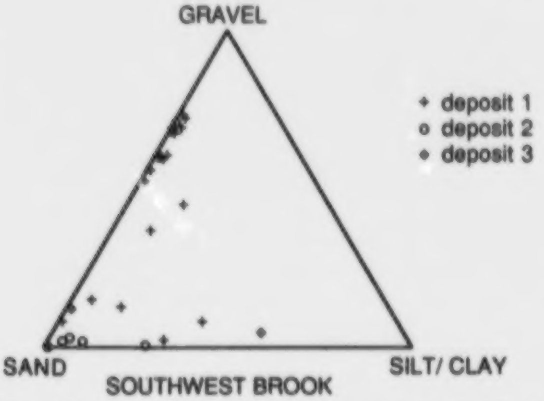

Figure 4. *Ternary diagram showing granular distribution of samples collected in deposits along Southwest Brook.*

to determine grain-size distribution and possible variations in deposit thickness.

Petrographic numbers (14 samples) range from 144 to 389 with an average of 252. The petrographic quality of this deposit is greatly reduced by the high content (55 percent) of slightly weathered to highly weathered sandstone, conglomerate, diorite, granodiorite and volcanic rocks. Fresh, hard granite, granodiorite and volcanics constitute the rest of the deposit. Variations in grain-size distribution and generally high petrographic numbers make this deposit unsuitable as a source of high-quality aggregate.

Deposit 2 is situated 4.5 km south of Lewisporte along Southwest Brook. This deposit is 900 m long, 500 m wide and 4 m thick. Six samples were taken from quarries and backhoe pits. Grain-size analyses of sampled material show an average of 39.9 percent gravel, 57.9 percent sand and 2.2 percent silt-clay. Samples showed variations of silt-clay from 0.75 percent to 9.82 percent with the exception of one silty-sand sample having a silt-clay content of 27 percent (Figure 4). Approximately 50 percent of this zone has been quarried. Most of the remaining material consists of silty sand and silt. Petrographic numbers for 3 samples analyzed in this deposit are 148, 183 and 293.

This zone is regarded as having low economic potential because of past removal, and the leaving behind of high silt-clay materials that have low economic value.

Deposit 3, located farther south along Southwest Brook than deposits 1 and 2, is approximately 6 km south of Lewisporte and is approximately 600 m long, 300 m wide and 5 m thick. Three samples collected from this area were taken from quarry exposures averaging 6 m in thickness (Plate 1). One sample was similar to a Class A road-gravel texture and two others consisted of fine to medium sand, and a fine sand and silt. Fine to medium sand is apparent along most exposures (approximately 65 percent), whereas Class A material was sampled in the east part of the quarry (approximately 20 percent of exposed material). The remaining material consists of silty sand (Figure 4), located in the southwest corner of the quarry. This area is currently being quarried to obtain a blending sand for use in concrete.

Plate 1. *Sand and sandy gravel in active quarry in Zone 3 near Southwest Brook.*

Only one sample taken from this zone contained material greater than 16 mm and can be used to determine petrographic qualities. A petrographic number of 327, which is a low-quality aggregate, was mainly due to the relatively high content (64 percent) of slightly weathered to intensely weathered sandstone, siltstone, granite, volcanic rocks, diorite and gabbro. The deposit also contains 36 percent fresh, hard volcanic rocks, diorite and gabbro.

This deposit may contain enough material to sustain the present operator for another 3 to 5 years at present removal rate (B. White, personal communications, 1990).

LILY POND

The Lily Pond deposit is a small outwash deposit located near the central part of map area 2E/3, 1 km south of Lily Pond (Figure 2). It is approximately 400 m long, 25 m wide and up to 1.5 m thick. It is in a region of dense forest growth underlain by approximately 0.6 m of topsoil and iron oxide. One sample was collected from a 1-m-deep backhoe pit. Grain-size analyses of the sampled material indicate that this deposit contains 1 percent gravel, 97.7 percent sand and 3.2 percent silt-clay. It has a dominantly fine sandy texture with 30 percent of the material between 0.25 and 0.5 mm in diameter. Petrographic examination of coarse aggregate was not possible. The small size of this deposit greatly reduces its economic potential.

KITE COVE

The Kite Cove deposit is a large delta formed at the northwest side of Kite Cove in the northern part of map area 2E/3 (Figure 2). This deposit is 800 m long, 300 m wide and up to 40 m thick. Dense forest growth covers most of this deposit. One sample was collected from a 20-m-high quarry exposure. Grain-size analysis of sampled material indicates it is similar to Class A type road gravel with size fractions from 1 to 64 mm forming 10 to 15 percent of sample weight. No material was collected in the +64 mm sieve but cobbles and boulders were observed along the 20-m-high-site exposure (Plate 2).

A petrographic number of 238 was determined from 23 percent moderately weathered to weathered siltstone, sandstone, conglomerate, tuff, granites and volcanic rocks, and 75 percent fresh to slightly weathered, hard, sandstone, gabbro and volcanic rocks.

Due to the size of this deposit, additional sampling is required to determine its quality and economic potential.

NORTHERN ARM

The Northern Arm deposit is located along Northern Arm Brook and around the community of Northern Arm in the west part of map area 2E/3 (Figure 2). This deposit covers a large area, extending over 8 km from Northern Arm in a southwest direction along both banks of Northern Arm Brook. The width of this deposit varies from 1 to 3 km and thickness from 1 to 12 m. It is situated in a area of dense forest growth, bog and minor cleared areas for farmland. Topsoil and iron-oxide layers may vary from 0.7 to 1.4 m in thickness. Bog cover has a thickness up to 2 m along the valley floor area of Northern Arm Brook. Twenty-eight samples were collected from this deposit from road and

Plate 2. *Gravel exposure in 40-m-high delta at Kite Cove.*

quarry exposures, stream cuts (Plate 3) and backhoe pits, averaging 3.5 m high. Grain-size analyses show variable textures from Class A type materials to silty sands (Figure 5). This deposit is estimated to contain 45 percent gravel, 54 percent sand and 1 percent silt-clay based on analysis of 28 samples (Table 2). Five other samples showed a range of 8.6 to 25 percent, but these analyses are not typical throughout the deposit. Past and present mining activity has removed large amounts of material from this deposit. However, due to its large size, several quarrying operations can operate in this area for many years at present excavation levels, without severely depleting the resource.

Petrographic analysis was conducted on 19 samples collected in the Northern Arm deposit. Petrographic numbers range from 119 to 340 with an average of 218. High petrographic numbers in the Northern Arm deposit result from weathering of normally hard rock types such as granite, norite and gabbro, making the pebbles softer and easily breakable. Sandstone and conglomerate are also present in this area and contribute to higher petrographic numbers.

This deposit can provide suitable low silt-clay aggregate appropriate for use in concrete and paving projects. However, selective mining is necessary due to the variable petrographic qualities throughout the deposit.

Plate 3. *Gravel in 3-m-high stream cut along Northern Arm Brook.*

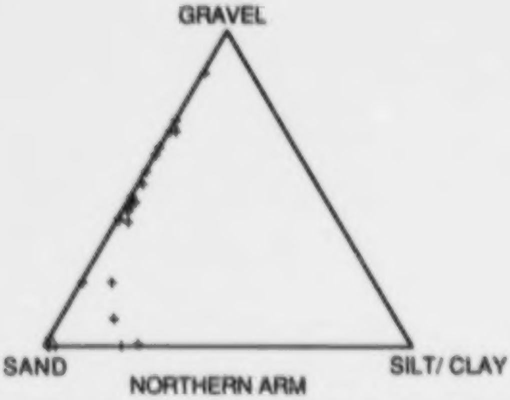

Figure 5. *Ternary diagram showing granular distribution of samples collected in glaciofluvial outwash material at Northern Arm.*

PETERS RIVER (NORTHEAST)

This large deposit stretches over 12 km, in a southwest direction from Peters Arm to beyond Peters Pond in the western part of map area 2E/3 (Figure 2). It varies from 0.2 to 1 km in width and has an estimated thickness from 6 to 25 m that averages about 13 m. Dense forest and minor cleared areas for farmland cover this deposit. Topsoil and iron-oxide layers may range from 0.5 to 1.2 m in thickness. Thirty-three samples were collected in this area from roadcuts, stream cuts, quarry exposures (Plates 4 and 5) and in backhoe pits averaging a depth of 4.9 m. Grain-size analyses show a wide range of textures with gravel content ranging from 0 to 90 percent. Silt-clay content is generally around 1 percent, although 5 samples have a silt-clay content between 5 and 15 percent (Figure 6). This deposit, based on analysis of 28 samples, is estimated to contain an average

Plate 4. *Sand quarry in glaciofluvial outwash deposit at Peters River.*

Plate 5. *Coarse gravel deposit (77 percent gravel) along 15-m-high quarry exposure in the northeast part of Peters River.*

of 43 percent gravel, 55.9 percent sand and 1.1 percent silt-clay.

Petrographic numbers range from 151 to 450 with an average of 273 (17 samples). High petrographic numbers result from slightly weathered to weathered sandstone, siltstone, volcanic rocks (80 percent average). The remaining rock types include fresh to slightly weathered, hard granites, gabbro, volcanic rocks and diorite.

The variable textures found throughout this deposit allow for a wide range of uses for this material. However, the petrographic qualities are generally poor and this will restrict its use in most concrete and road-paving projects.

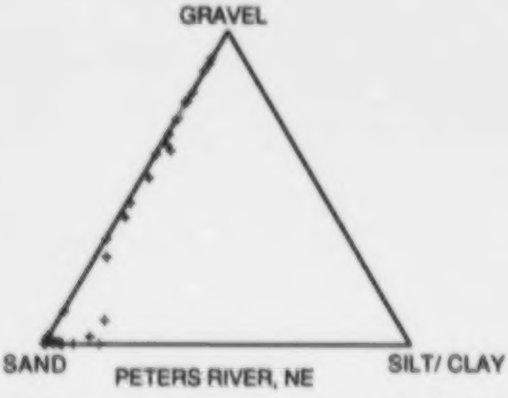

Figure 6. *Ternary diagram showing granular distribution of samples collected in glaciofluvial material at Peters River (northeast).*

EXPLOITS RIVER

The lower part of the Exploits River is situated in the southwest corner of map area 2E/3. The banks of this river consist of an extensive deposit of glaciofluvial outwash material, over 11 km in length and up to 10 m thick. It is overlain by dense forest growth and bog. Extensive cabin development has occurred on the southeast bank of the river. This area can be divided into 4 different zones (Figure 2), each having differing grain-size distributions (Table 2).

Zone 1 is located on the northeast bank near the mouth of the river in the Bay of Exploits at Wigwam Point. It is approximately 1200 m long, 150 m wide and 1 to 5 m thick. Dense forest growth and residential development cover this zone. In this area, topsoil and iron-oxide layers average 0.6 m in thickness. Three samples collected in this area were taken from riverbank exposures averaging 3.6 m thick. Grain-size analyses of sampled material in this area indicate that gravel content varies between 30 and 56 percent, sand content varies between 38 and 70 percent, and silt-clay content is less than 0.5 percent (Figure 7).

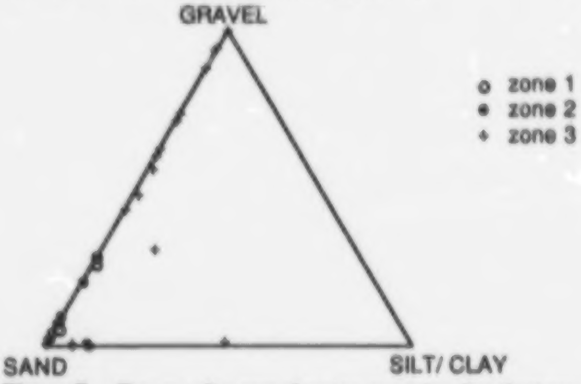

Figure 7. *Ternary diagram showing granular distributions of samples collected in Zones 1, 2 and 3 along the Exploits River.*

Petrographic characteristics are poor, as indicated by high petrographic numbers of 408, 436 and 482. Poor petrographic quality, residential development on part of this deposit, and its thin occurrence in some areas may make it uneconomical for large-scale mining activity.

Zone 2 is also located on the northeast bank of the Exploits River; it extends to the southwest from Zone 1, for a distance of 6 km. It is approximately 300 m wide and has a thickness of 8 m. Bog covers most of this zone. Bedrock exposures protrude through the deposit at two locations. Nine samples collected in this area were taken from stream cuts having an average thickness of 8 m (Plate 6). The deposit, determined from the analysis of 7 samples, is estimated to contain an average of 7.3 percent gravel, 92.6 percent sand and 0.1 percent silt-clay. Two samples collected in the southwest part of this zone contain 88 percent sand and 12 percent silt-clay (Figure 7). Throughout the zone, the sand is generally fine, having fractions from 0.25 mm to 0.5 mm, which make up between 35 to 75 percent sediment. Due to the fine texture of this zone, no petrographic analyses could be conducted.

Plate 6. *Ten-metre-high sand exposure in Zone 2 along the Exploits River.*

High silt-clay content (11 percent) in the southwest part of this deposit will restrict its use and low gravel content makes it unsuitable for road gravel. If petrographic qualities are determined to be satisfactory, it could be used in asphalt as a blending sand or winter road sand.

Zone 3 is located on the northwest bank of the Exploits River adjacent to the southwest boundary of Zone 2 and 300 m northeast of the Trans-Canada Highway. Zone 3 is 3000 m long, 200 to 1000 m wide and varies from 2 to 12 m in thickness. It is covered by bog, low bush and tree growth. Bog cover is up to 2 m thick in some areas. Eighteen samples collected in this zone were taken from roadcuts, stream cuts, quarry exposures and backhoe pits averaging 3 m in thickness. This zone is estimated to contain an average of 65.5 percent gravel, 34.0 percent sand and 0.5 percent silt-clay based on analyses of 14 samples. Four other samples showed silt-clay content ranging from 7 to 48 percent (Figure 7). However, these four samples are not a typical representation of material and were not included in average analysis. This deposit has been extensively quarried in the past and most of the remaining material is covered by bog.

Petrographic analyses of 12 samples from Zone 3 has shown high proportions of soft, friable pebbles resulting from slight to high weathering. Pebble types affected by weathering include sandstone, tuff, phyllites, pelitic schist, and minor amounts of volcanic rocks and granites, totalling 65 percent of all samples. Hard, fresh pebbles consisting of gabbro and sandstone make up the remaining 35 percent. Petrographic numbers range from 185 to 704 with an average of 406.

Quarrying at present removal rates may be able to continue for some time, however, localized areas of high silt-clay content and thick bog cover will hinder quarrying, and poor petrographic quality will restrict its use.

Zone 4 is located on the southeast bank of the Exploits River between Rattling Brook and Jumpers Brook in map area 2E/3 (Figure 2). Zone 4 is approximately 9000 m long, 300 to 1000 m wide and up to 10 m thick. This zone is covered by cabin development, moderate tree growth and low bush cover, and small areas of bog and farmland; topsoil and iron-oxide layers average 0.8 m in thickness. Thirty-one samples were collected in this area, from stream cut, quarry exposures and backhoe pits averaging 2.5 m thick. This deposit is estimated to contain an average of 37.3 percent gravel, 62.2 percent sand and 0.5 percent silt-clay based on analyses of 30 samples. One other sample had a silt-clay content of 41 percent (Figure 8), which is not typical of exposed material throughout the zone. The northwest and north sections of this zone are covered by extensive cabin development. Quarrying in the past has removed considerable amounts of material from parts of this area and has uncovered bedrock near surface levels in some areas.

Petrographic analyses of 21 samples from this area has shown that the pebble fraction contains an average of 87 percent slightly weathered sandstone and 13 percent highly weathered unidentified pebbles. Petrographic numbers range from 140 to 498 with an average of 270.

Cabin development and farmland will reduce access to most of this area. Although grain-size analyses indicate Zone 4 to be an excellent source of low silt-clay aggregate, petrographic qualities are too poor to allow this material to be used in most concrete or road-paving-type projects. The possibility of locating bedrock in unquarried areas will reduce the estimated quantity given in Table 1.

JUMPERS BROOK

The Jumpers Brook deposit is a delta located near the southwest corner of map area 2E/3 (Figure 2). It is

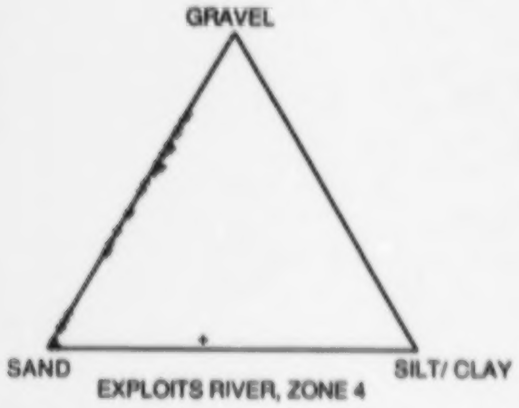

Figure 8. *Ternary diagram of samples collected in Zone 4 along the Exploits River.*

approximately 1800 m long, 200 m wide and 5 m thick. Forest growth, which covers this deposit, is underlain by a 0.8 m layer of topsoil and iron oxide. In this area, five samples were collected from quarry exposures averaging 4 m in thickness (Plate 7). Generally, this deposit consists of compacted sandy gravel and sand, and fine sand and silt in the north end of the deposit. Iron-oxide staining is a common characteristic throughout gravel. This deposit is estimated to contain 36.2 percent gravel, 59.5 percent sand and 4.3 percent silt-clay based on analyses of 5 samples. Gravel content ranges from 1 to 74 percent, sand from 24 to 92 percent and silt-clay from 0.5 to 11.1 percent.

Petrographic analyses of 3 samples has shown 46 percent pebbles consist of slightly weathered to intensely weathered diorite, granites, volcanic rocks and sandstone, and 54 percent consist of fresh, hard diorite, granites, gabbro, volcanic rocks, quartz pebbles and sandstone. Petrographic numbers of these samples are 176, 178 and 282.

Iron-oxide staining occuring throughout parts of this gravel and sand deposit, and poor petrographic qualities, make this deposit unsuitable for high-quality aggregate.

2E/4 MAP AREA

PETERS RIVER (SOUTHWEST)

The southwest part of Peters River is located in the southeast corner of map area 2E/4. The river flows through a large glaciofluvial outwash deposit over 9 km long and varying between 150 to 1600 m wide. It is covered by dense forest growth, farmland and bog. This deposit can be divided into 2 zones (Figure 2) based on grain-size analyses (Table 2, Figure 9).

Zone 1 consists of a large sand deposit, 4000 m long, 1600 m wide and estimated to be 8 m thick. Three samples were collected from shallow roadcuts averaging 0.6 m in thickness. This zone is estimated to contain 11 percent gravel, 80 percent sand and 9 percent silt-clay based on the analyses of sampled material; silt-clay ranges from 1.4 to 19.3 percent in these samples (Figure 9).

Plate 7. *Compacted gravel and sand in delta deposit at Jumpers Brook. Iron-oxide staining is a common characteristic throughout sediment in this area.*

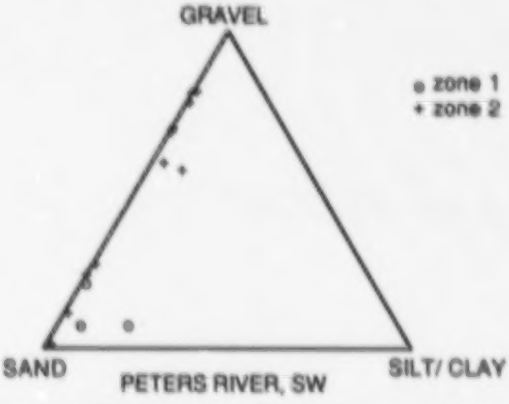

Figure 9. *Ternary diagram showing granular distribution in Zones 1 and 2 in the southwest part of Peters River.*

Petrographic analyses of one sample indicate poor petrographic quality having a petrographic number of 455.

Variable silt-clay content, and poor petrographic qualities based on one sample, make it necessary to have further sampling to determine the deposit's potential. Farmland development and a tree nursery may prevent quarrying activity in most of this area.

Zone 2 is located southwest of Zone 1 and crosses New Bay Pond Road. It is 4 km long, 0.2 to 1.1 km wide and has an estimated thickness of 6 m. Zone 2 contains more gravel than Zone 1 (Table 2) and has been extensively quarried in the past. Twelve samples collected in this area were taken from roadcuts, quarry exposures, and backhoe pits averaging 2.5 m in thickness. Grain-size analyses of sampled material (Figure 9) indicate this zone contains an average of 51.8 percent gravel, 46.7 percent sand and 1.5 percent silt-clay.

Petrographic analyses of 9 samples indicate that 28 percent of the sample is moderately weathered to highly weathered sandstone, siltstone, conglomerate and undefined pebbles. The remaining 62 percent consists of fresh, hard granites, volcanic rocks, gabbro, chert and diorite. Petrographic numbers range from 146 to 503 and have an average of 286.

Grain-size analyses indicate this deposit is a good source of low silt-clay aggregate, however, poor petrographic qualities make it unsuitable for use in concrete or road-paving-type projects.

HODGES HILL

The Hodges Hill deposit is located in the west part of map area 2E/4, 2 km south of Hodges Hill (Figure 2). This deposit is approximately 1200 m long, 600 m wide and 2 to 5 m thick. Bedrock and till hummocks protrude through the gravel at several locations. Moderate forest growth covering this deposit is underlain by a 0.5 m layer of topsoil and iron oxide. Two samples collected in this area were taken from the base of a 2-m-deep bulldozed pit, and from a 1-m-high roadcut. Grain-size analyses of sampled material show a range of 48 to 75 percent gravel, 25 to 52 percent sand and less than 1 percent silt-clay. Visual observations indicate approximately 25 to 35 percent boulder–cobble material, with surface boulders up to 1.8 m thick.

Petrographic analyses of two samples indicate the Hodges Hill deposit is composed of 36 percent slightly weathered to weathered siltstone, sandstone, granites and volcanic rocks. The remaining 64 percent consist of fresh, hard sandstone, granites, diorite, and volcanic rocks. The petrographic numbers of these two samples are 150 and 156.

Crushing or screening will be needed in this deposit to remove the coarse aggregate fraction, if it is to be used in road paving or as a Class A road gravel. Petrographic numbers indicate this material is unsuitable for concrete purposes.

ASPEN POND

The Aspen Pond deposit is located at the north end of Aspen Pond near the southwest corner of map area 2E/4 (Figure 2). This deposit is approximately 700 m long, 150 m wide and 3 m thick. Moderate forest growth in this region is underlain by a 0.6-m-thick layer of topsoil and iron oxide. One sample was collected from a 1.8-m-deep bulldozed pit. Forty percent boulder–cobble content was estimated visually. Grain-size analyses of sampled material show 86.8 percent gravel, 13 percent sand and 0.2 percent silt-clay.

Petrographic analyses of sampled material has shown 64 percent highly and weathered sandstone and 36 percent fresh to slightly weathered granite and volcanic rocks. A petrographic number of 224 was determined for this sample.

Grain-size analyses indicate this deposit is favourable as a source of low silt-clay type material, but poor petrographic qualities and high boulder–cobble content reduces its economic potential.

CORNFIELD POND

The Cornfield Pond deposit is located at the north end of Cornfield Pond in the southwest corner of map area 2E/4 (Figure 2). It consists of a small glaciofluvial terrace deposit, approximately 300 m long, 200 m wide and 2.5 m thick. Forest growth and minor bog cover overlie this deposit. Topsoil and iron-oxide layers have an average thickness of 0.8 m. One sample was collected from a 2.5-m-high quarry exposure. This exposure consisted of approximately 30 percent cobbles and boulders and localized sand lenses. Grain-size analysis of this sample showed 67.9 percent gravel, 31.8 percent sand and 0.3 percent silt-clay.

A petrographic number of 106 was determined for one sample. The pebble fraction consists of 94 percent fresh, hard volcanic rocks, gabbro and granites and 6 percent weak, soft conglomerate.

Although petrographic characteristics of this deposit are favourable for all types of high-grade aggregate uses, its potential is reduced by its high cobble–boulder content and small size.

MOOSE POND

The Moose Pond deposit adjoins the northeast side of Moose Pond, on the west side of map area 2E/4 (Figure 2) and consists of a shallow glaciofluvial outwash deposit. Its approximately 1 km long, 0.2 km wide and 2 m thick. Forestry operations have removed tree cover from this area. Topsoil and iron-oxide thickness vary from 0.3 to 0.7 m in thickness. Sections throughout the deposit show sand and silt lenses, and areas consisting of 30 to 40 percent boulder and cobble material. Three samples were taken from bulldozed pits and a roadcut, each averaging 2 m in thickness. Grain-size analyses of sampled material indicate variable textures. One sample contained 81 percent coarse sand material (< 2 mm in diameter), and 19 percent silt-clay. Another sample showed a coarse texture having 22 percent of the material in the 64 mm sieve, and the third sample showed a more even distribution (10 to 15 percent) of material throughout most sieve fractions and dropping to 3.2 percent in the pan fraction. All samples contained more than 3.2 percent silt-clay.

Petrographic analyses of sample material show poor characteristics with pebble types consisting of 38 percent poor quality sandstone, diorite, and volcanic rocks. The remaining 62 percent consist of fresh, durable volcanic rocks, granite, gabbro and quartz pebbles. The petrographic numbers of 2 samples collected in this area are 168 and 202.

Small size, shallow thickness, variable texture and poor petrographic qualities greatly reduces the economic potential of this deposit.

MAP AREA 2E/6

BROWNS ARM

The Browns Arm deposit is located at Browns Arm in the area lying at the border between map areas 2E/6 and 2E/3 (Figure 2). This deposit consists of a large delta, 1.5 km long, 0.7 km wide and up to 50 m thick. Rock outcrop protrudes the centre of this deposit, covering about 10 percent of the surface area. Approximately 50 percent of the area is cleared for farmland, and peripheral areas on the east and north sides are residential. Areas of dense forest growth cover smaller sections. This deposit contains variable interbeds of sandy gravel, gravel, cobble gravel and silty sand (Plate 8). Seven samples were taken from quarry exposures, averaging 14 m high. It is estimated to contain an average of 51.4 percent gravel, 47.6 percent sand and 0.9 percent silt-clay based on grain-size analyses of 6 samples (Figure 10). Another sample had a silt-clay content of 18.7 percent but this does not represent typical sections throughout the deposit.

Petrographic analyses of 3 samples indicate poor-quality material with approximately 54 percent of the pebbles consisting of slightly to highly weathered sandstone, gabbro, volcanics, conglomerate and undefined pebbles. Petrographic numbers of 4 samples range from 213 to 457 with an average of 324.

Grain-size analyses indicate this deposit may provide an excellent source of low silt-clay and Class A aggregate used in road construction, but poor petrographic qualities reduce its potential as a source of higher quality material for use in concrete and road-paving projects.

DIVER POND

The Diver Pond deposit is situated southwest of Diver Pond in the west part of map area 2E/6 (Figure 2). This is a shallow glaciofluvial outwash deposit, 1.3 km long, 0.3 km wide and 1.5 m thick. Moderate tree growth and low bush growth cover most of this deposit. Topsoil and iron-oxide layers average 0.6 m in thickness. Two samples were collected in this area, from a 2.5-m quarry exposure and from a 1-m-deep hand-dug pit. This deposit is estimated to contain 74 to 79 percent gravel, 21 to 26 percent sand and less than 1 percent silt-clay based on analyses of sampled material.

Petrographic analyses of 2 samples indicate 62 percent of the pebbles in this deposit are slightly weathered to weathered volcanic rocks, gabbro, granite, sandstone and siltstone. The remaining 38 percent consist of fresh, durable volcanic rocks, gabbro, granite and siltstone. Petrographic numbers of these 2 samples were 236 and 248.

Shallow thickness and poor petrographic qualities gives this deposit low economic potential.

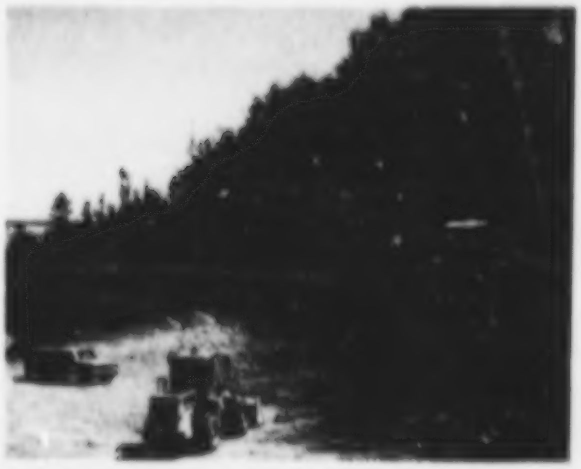

Plate 8. *Sandy gravel, gravel and cobble–gravel visible along 20-m-high quarry exposure in the Browns Arm delta deposit.*

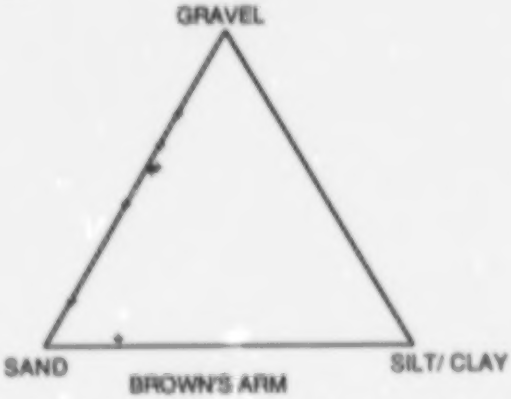

Figure 10. *Ternary diagram showing granular distribution of samples collected in a delta at Browns Arm.*

NEW BAY RIVER

The New Bay River deposit is located along New Bay River in the southwest part of map area 2E/4 (Figure 2). This deposit is approximately 1.5 km long and 0.3 km wide and may vary from 0.1 m to 7.0 m thick. Moderate forest growth covers the top of this deposit. Three samples were taken from road exposures averaging 2.5 m thick. Grain-size analyses of sampled material indicate this deposit is composed of sandy gravel to sand, averaging 25.7 percent gravel, 73.2 percent sand and 0.1 percent silt-clay. Gravel contents range from 13 to 31 percent, sand from 66 to 87 percent and silt-clay from 0.5 to 2.4 percent.

Petrographic analyses indicate very poor quality material with petrographic numbers of 438 and 517.

Low volumes and poor petrographic qualities give this deposit poor economic potential.

POINT LEAMINGTON

The Point Leamington deposit is situated in the community of Point Leamington on the west side of map area 2E/6 (Figure 2). This area consists of a delta approximately 490 m long, 250 m wide and up to 12 m thick. Forest growth, residential development and a graveyard occupy the top of this deposit. Topsoil and iron-oxide layers average about 0.7 m in this area. A silt-sand lens, low boulder content (less than 20 percent), and 4 to 6 percent silt-clay in a 4-m-thick upper gravel unit, were noted in the field. The exposed surface of the sand-silt unit is 10 m wide and 4 m high, and the silty gravel unit is approximately 25 m long and covers the top 3 m of half of the quarry face. Although textures may vary throughout the deposit (Figure 11), sample data generally indicate it is similar to Class A gravel. Six samples were taken from quarry exposures averaging 5.5 m (Plate 9). This deposit is estimated to contain an average of 46.6 percent gravel, 50.5 percent sand and 2.9 percent silt-clay based on analyses of sampled material.

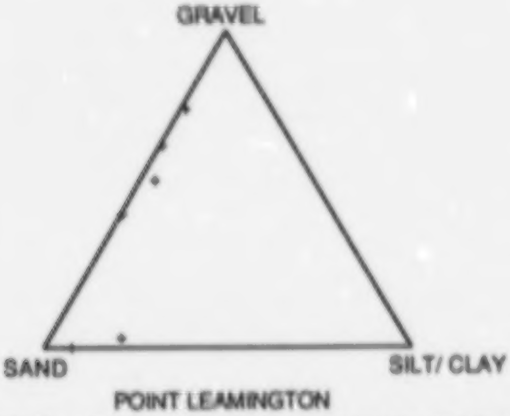

Figure 11. *Ternary diagram showing granular distribution of samples collected in delta deposit at Point Leamington.*

Plate 9. *Seven-metre-high quarry exposure in delta deposit at Point Leamington.*

Petrographic analyses of 4 samples indicate poor quality with pebbles consisting of 62 percent slightly weathered to weathered sandstone, gabbro, volcanic rocks, siltstone and granite. The fresh durable pebbles consist of volcanic rocks, siltstone and quartz. Petrographic numbers in the Point Leamington deposit range from 213 to 457 with an average of 324.

Grain-size analyses indicate this deposit can be used as a source of low silt-clay aggregate. However, poor petrographic qualities reduce its potential as a higher quality aggregate necessary for use in concrete or road-paving-type projects.

MARTIN POND

The Martin Pond deposit is located on the northeast side of Martin Pond in the west part of map area 2E/6 (Figure 2). This deposit is approximately 800 m long, 600 m wide and 2 m thick. Moderate tree growth and a small bog cover this deposit. Topsoil and iron-oxide layers average about 0.8 m in thickness. Two samples were collected from 1.5-m and 3.8-m-high quarry exposures. This deposit is similar to Class A gravel, having grain sizes peaking in the 8 to 16 mm range, constituting 23 percent of the sample. Grain-size analyses of sampled material showed 57 to 71 percent gravel, 28 to 42 percent sand and 0.3 to 1.1 percent silt-clay.

Petrographic analysis of one sample indicates poor quality material due to the presence of 54 percent slightly weathered to weathered gabbro, volcanic rocks and granite pebbles. The remaining 46 percent consist of fresh gabbro, sandstone, volcanic rocks and quartz pebbles. Petrographic numbers of two samples in the Martin Pond deposit were 152 and 534.

Grain-size distribution indicate this deposit can be used as a Class A road gravel but its shallow thickness and poor petrographic qualities reduce its economic potential.

OTHER DEPOSITS

Besides the areas sampled and outlined above, 4 other potential resource areas were noted from aerial photograph interpretation but were not field checked. These deposits will be sampled during the 1991 field season. Three of these deposits are located in the 2E/3 map area, at Joe's Cove in the Bay of Exploits, Burnt Arm, and 5 km northwest of Upper Scissors Pond. One other potential deposit is located in the 2E/4 map area, along Leech Brook (Figure 2).

SUMMARY

Granular deposits were sampled at many locations within the study area to determine their potential for use in the aggregate industry. The results reveal differences between these deposits that may determine their suitability for various construction purposes. The data is based on grain-size analyses, and petrographic examination of the pebble fraction (16 to 32 mm) from samples collected in each deposit.

Several deposits are thin (around 2 m) and would require extensive overburden clearing to quarry small amounts of material, thereby increasing excavating cost. Deposits of this type are located at Cornfield Pond, Aspen Pond, Moose Pond, Hodges Hill, Lily Pond, Diver Pond and New Bay River.

Many of the deposits sampled have sufficient quantities of material to support large quarrying operations over a considerable length of time (exceeding a 10-year production period). These deposits, located at Peters River, Browns Arm, Northern Arm and Kite Cove, may exceed 10,000,000 m^3 of material. Other large deposits are located at Jumpers Brook and Point Leamington. These deposits have been extensively mined in the past but are estimated to have between 500,000 m^3 and 1,000,000 m3 of material remaining.

Low silt-clay content is necessary for aggregates used in concrete projects and asphalt. Most deposits sampled have a silt-clay content of less than 1 percent. Other deposits may have zones of sand-silt or silt-clay, which can be avoided during quarrying. This reduces the need for washing the material, thereby reducing overall cost. In some areas, screening or crushing may be necessary to remove the coarse aggregate fraction.

Petrographic results indicate generally poor quality material throughout the study area. Only two deposits show petrographic numbers low enough to indicate suitable aggregate material for use in concrete or asphalt type projects. These are thin deposits located at Cornfield Pond and Hodges Hill. Two other deposits, where multiple samples were collected, show variable petrographic qualities, in which some of the samples are within acceptable petrographic limits, to allow high-quality aggregate use. These deposits are located at Northern Arm and Southwest Brook. In these areas, detailed sampling is necessary to locate suitable zones for quarrying.

ACKNOWLEDGMENTS

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REFERENCES

Andrews, K. (compiled by)
1980: Mineral occurrence map, Botwood. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 80-4.

ASTM Standards
1990: Annual Book of ASTM Standards Section 4, Construction, Volume 04.02, Concrete and Aggregates, C88-83, C131-89.

Bragg, D.J.
This volume: Bedrock aggregate surveys in the Bull Arm–Mosquito Cove area, Trinity Bay, and central Newfoundland.

1986: Geotechnical bedrock compilation maps of Newfoundland. Scale 1:250,000 (supplemental Report 83-2). Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Nfld (1485).

1990: Reconnaissance assessment of bedrock aggregate in central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 7-11.

Canadian Standards Association
1973: CSA standard A23.2.30, Rexdale, Ontario, pages 207- 209.

Carter, P.D.
1981: The Economics of Mineral Aggregate Production and Consumption in Newfoundland and Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, St. John's, Newfoundland, 112 pages.

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. (Compilers)
1990: Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-01.

Dean, P.L.
1977: A report on the geology and metallogeny of the Notre Dame Bay Area, to accompany metallogenic maps 12H/1,8,9 and 2E/3,4,5,6,7,9,10,11 and 12. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-10, 17 pages.

Environmental Geological Section
1983: Site data and 1:50,000 scale maps. Field maps for all surficial and glacial mapping and aggregate resource mapping projects. Newfoundland Department of Mines and Energy, Mineral Development Division, Open file NFLD (1267).

Kirby, F.T., Ricketts, R.J. and Vanderveer, D.G.
1983: Inventory of aggregate resources of Newfoundland and Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 83-2, 36 pages.

1989: Selected geomorphological maps of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File NFLD (1693).

Department of Transportation
1987: Specifications Book, Tendering Section, St. John's, Form 315 and Form 904, 12 pages.

Ricketts, M.J.
1987: Coastal Labrador aggregate resources. Newfoundland Department of Mines and Energy, Mineral Development Division, St. John's, Mineral Resource Report #5, 50 pages.

Vanderveer, D.G.
1982: Municipal planning and aggregate resources – a brief synopsis. Newfoundland Department of Mines and Energy, Mineral Development Division, unpublished report, 2 pages.

1983: Aggregates – the often maligned and often forgotten mineral. *In* 19th Forum on the geology of industrial minerals. Proceedings. *Edited by* S.E. Yudt. Ontario Geological Survey, Miscellaneous Paper 114, pages 65-78.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 61-68

REGIONAL STRIATION SURVEY AND DEGLACIAL HISTORY OF THE NOTRE DAME BAY AREA, NEWFOUNDLAND

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Terrain Sciences Section

ABSTRACT

Results from reconnaissance-striation mapping in the Notre Dame Bay area, north-central Newfoundland (covering NTS map areas 2E/2, 3, 6, 7, 9, 10, 11 and the east half of 2E/4 and 5) suggest a complex ice-flow history for the area, having at least four separate ice-flow events. The earliest ice-flow direction was east-southeast, followed by a second ice-flow direction trending north-northeast. The third ice-flow event ranged from a northeast flow in the west of the study area to a northwest flow in the east. Evidence for these first three events has been found over most of the study area. The most recent ice-flow event was a local, small-scale east-southeast-trending event recorded only in the west of the study area.

This study represents the most detailed regional reconnaissance-striation survey conducted in the area, upon which a tentative new re-interpretation of the glacial history of the region is made. Coalescence of ice caps, centred on the Northern Peninsula and in central Newfoundland occured during the Late Wisconsinan glacial maximum. As deglaciation progressed, the central Newfoundland ice-cap initially separated from the Northern Peninsula ice-cap and subsequently split into at least three ice-centres. Final decay of the central Newfoundland ice cap resulted in minor ice-centres, which may have briefly readvanced.

INTRODUCTION

The Notre Dame Bay area is a region of considerable mineral exploration interest, especially for gold and base metals. Mineral exploration has been hampered by extensive overburden and a lack of information on the Quaternary geology of the region. A thorough understanding of the Quaternary ice-flow history could enhance efforts to trace mineralized float and geochemical anomalies detected in the overburden, to potential target areas.

Glacial striations are small grooves or scratches cut into the bedrock surface by rock fragments carried at the base of a glacier (Sugden and John, 1976). The orientation of these striations represent a record of the ice-flow direction at the time of their formation. Variations may occur in the orientation of individual striations, however, a compilation of striation sites may indicate a pattern of ice flow.

This striation-mapping project is intended to provide rapid regional coverage of areas with mineral potential much sooner than the more detailed but slower 1:50,000-scale surfical mapping program. Striation mapping is an effective method of obtaining a broad understanding of the (deglacial) ice-flow history over a wide regional area.

OBJECTIVE

The project objective is to conduct a reconnaissance-level mapping of glacial striations, at a 1:50,000 scale, of NTS map areas 2E/2, 3, 6, 7, 9, 10, 11 and the east half of 2E/4 and 5 (Figure 1).

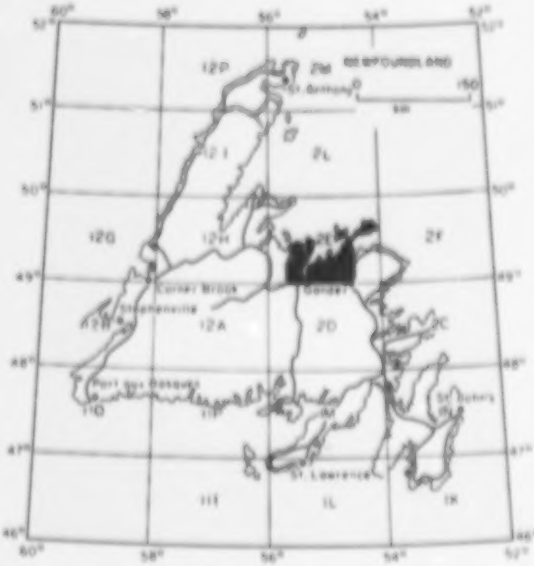


Figure 1. *Index map.*

PREVIOUS WORK

Jenness (1960), based on surfical mapping in the Terra Nova–Bonavista Bay area, suggested that ice flowed eastward across most of eastern Newfoundland from a source to the west of the Bay of Exploits. Prest *et al.* (1968) report a northeasterly oriented ice-flow for the Gander Lake area and north-central Newfoundland. Grant (1977) proposed a north-northeast ice flow for north-central Newfoundland during the Late Wisconsinan maximum, from an ice cap in central Newfoundland. Ice-flow indicators have also been recorded in the region by bedrock and surfical mappers including MacClintock and Twenhofel (1940), Baird (1950), Hayes (1951), Lundqvist (1965), Hornbrook *et al.* (1975), Vanderveer and Sparkes (1980), Vanderveer (1983, 1987), Vanderveer and Taylor (1987), Proudfoot *et al.* (1988), Liverman and St. Croix (1989a), Taylor and St. Croix (1989), Batterson *et al.* (1991) and Liverman *et al.* *(this volume)*.

Prest (1970) attributed a minimun of five and probably more ice-dispersal centres to the Island of Newfoundland. Grant (1974) suggested that the main Newfoundland ice cap split into fifteen remnant ice centres during deglaciation. Five of these remnant ice centres had the potential to influence ice-flow in north-central Newfoundland. Three of these ice centres were located in central Newfoundland, near Red Indian Lake, Meelpaeg Lake, and in the Middle Ridge area. The fourth was north of Grand Falls in the Twin Ponds area and the fifth was located near Gander.

Summaries of the glacial history of Newfoundland are given by Tucker (1976), Grant (1977, 1989), Rogerson (1982) and Brookes (1982).

FIELD METHODS

Field work consisted of truck traverses along all primary and secondary roads and all-terrain vehicle traverses along most logging and winter roads. All exposed bedrock surfaces were examined for striations and other erosional ice-flow indicators. Approximately 425 single or multiple striation sites were found and recorded during the 1990 field season (Taylor and St. Croix, 1990). Ice-flow direction, where possible, was determined from the morphology of the bedrock surface using such features as stoss and lee, nailheads, chattermarks and miniature crag and tails. Sites that contain two or more striation directions are intrepreted to be the result of either separate glacial advances or different ice-flow directions within one flow event. Relative temporal relationships between separate flows on multiple direction sites are indicated by crosscutting features and leeside preservation.

The data has been entered into a striation database and is available upon request.

RESULTS

The field data suggests four separate ice-flow events affecting the Notre Dame Bay area; Figure 2 shows distribution of these sites. The earliest ice-flow event trends east-southeast and was observed at between 10 and 15 percent of the field sites. The second ice-flow direction showed a consistent north-northeast orientation over the entire study area. The third ice flow was oriented to the northeast, in the west of the field area and northwest in the east. The orientation of this third ice-flow event varies along it's path, especially toward the coast, and probably reflects topographic control. The fourth, and possibly most recent ice flow, was a local east-southeast-trending event that occurred west and south of the Bay of Exploits. The absolute age of these ice-flow events is unknown.

INTERPRETATION

FIRST ICE-FLOW EVENT

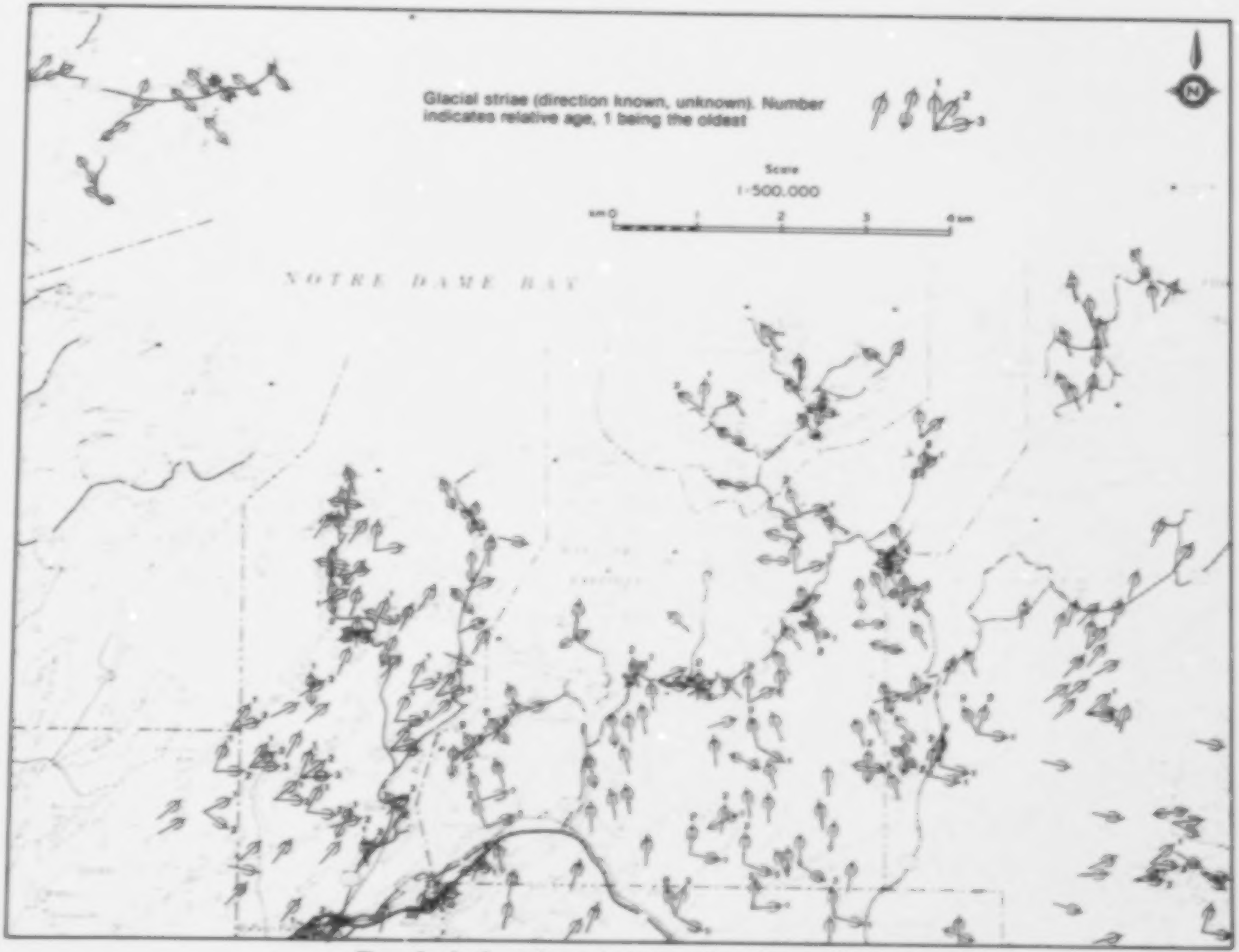
The east-southeast ice flow is the first of the four glacial events recorded (Figure 3). Ice-flow indicators that pertain to this ice-flow event have consistently been preserved on the leeside surfaces of outcrops that show one or more subsequent ice-flow events. One of the earliest references to this flow was by Murray (1882) who noted that massive blocks removed from the parent rock of Mount Peyton were dispersed eastward along the southeast and eastern flank of the mountain. Jenness (1960) working in the Terra Nova–Bonavista map area proposed that ice from west of the Bay of Exploits flowed across all of eastern Newfoundland. In the Gander Lake–Mount Peyton area, east-oriented striations were also mapped to the south of the field area by Taylor and St. Croix, (1989) and Batterson *et al.* (1991), and to the east of the study area near Weir's Pond by Vanderveer (1987).

Further work is required west of Grand Falls to establish if this initial east-southeast flow is related to the Red Indian Lake dispersal centre proposed by Grant (1974). The relationship of this east-southeast ice flow to striations recorded in the Great Gull Lake area (Vanderveer, 1983) and in the Millertown area (MacClintock and Twenhofel, 1940; Vanderveer and Sparkes, 1980) also needs re-examination.

Ice flows in response to gravity and should flow downslope (Paterson, 1981). The first ice flow follows an east-southeast course across northeastern Newfoundland rather than toward the coast and into Notre Dame Bay. An explanation for this behaviour is that ice may have flowed from the Northern Peninsula into Notre Dame Bay causing a deflection of ice flowing from the Red Indian Lake area eastward toward Bonavista Bay. Evidence for the east-southeast-oriented striations have been found on the Horse Islands, to the north of the Baie Verte Peninsula during the 1989 field season (Terrain Sciences Section, unpublished data) and in the La Scie area of the Baie Verte Peninsula (Liverman and St. Croix, 1989a). The relative chronology of these events is not known.

SECOND ICE-FLOW EVENT

The second ice flow has a north-northeast trend and is relatively consistent over the entire study area (Figure 4). Striations indicating a similiar flow direction have been mapped in and around the field area by Baird (1950), Hayes (1951), Lundqvist (1965), Hornbrook *et al.* (1975), Vanderveer and Sparkes (1980), Vanderveer (1983, 1987), Vanderveer and Taylor (1987), Taylor and St. Croix (1989) and Batterson *et al.* (1991).


Glacial striae (direction known, unknown). Number indicates relative age, 1 being the oldest
1
2
3
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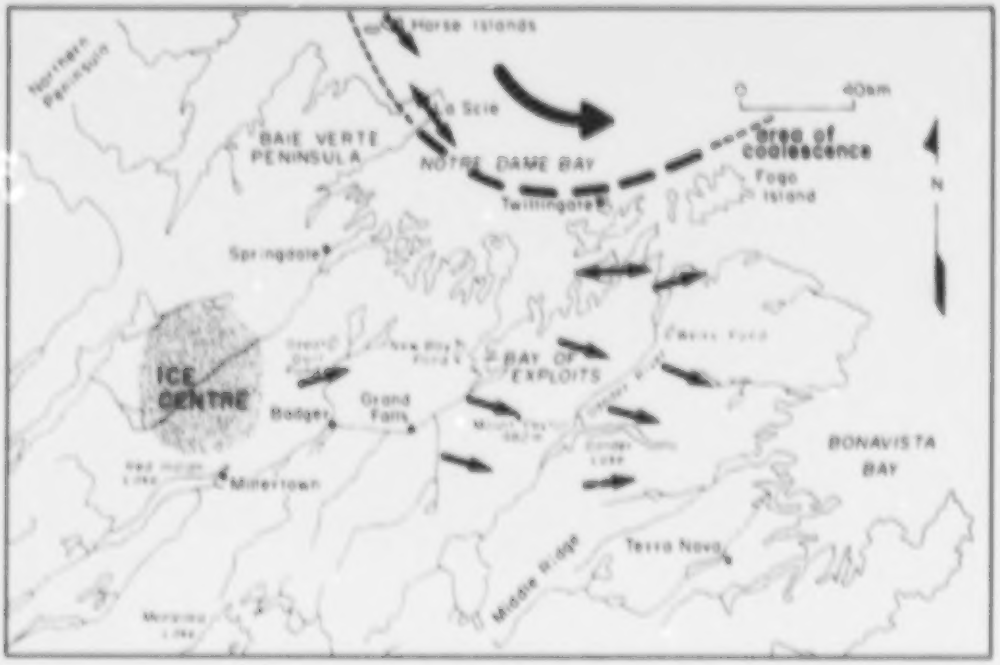
NOTRE DAME BAY

Figure 2. *Ice-flow indicators in the Notre Dame Bay area, Newfoundland.*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Badger
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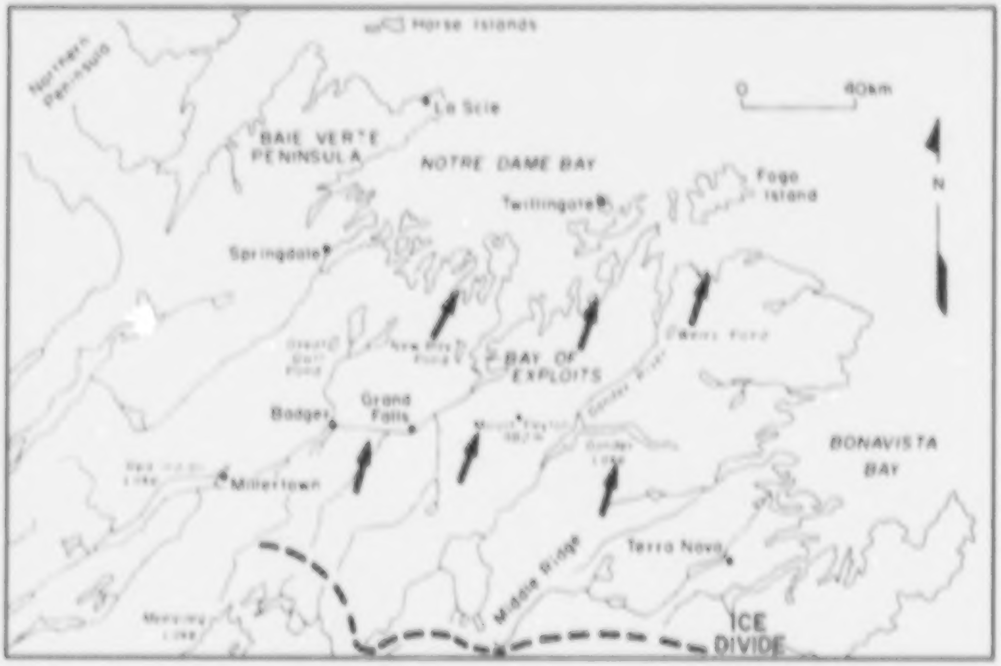
BAY OF EXPLOITS
Gander Lake
BONAVISTA BAY
Millertown
Terra Nova
Middle Ridge

Figure 3. *First ice-flow event.*


Horse Islands
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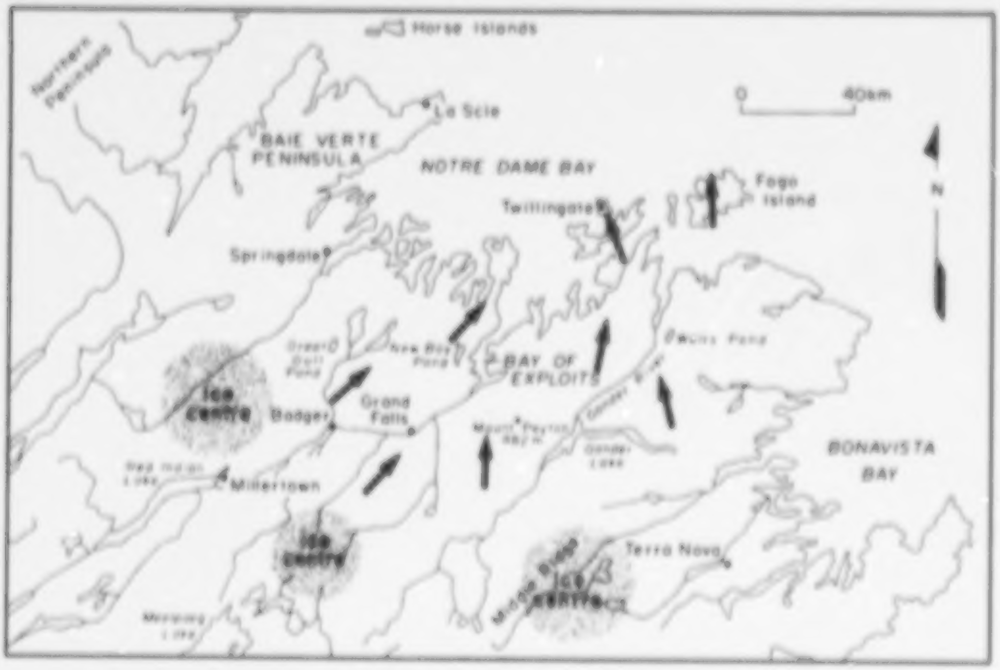
Badger
Grand Falls
BAY OF EXPLOITS
Gander Lake
BONAVISTA BAY
Millertown
Terra Nova
Middle Ridge
ICE DIVIDE

Figure 4. *Second ice-flow event.*

Prest *et al.* (1968), Grant (1977) and Rogerson (1982) indicated that a northeast ice flow was dominant in north-central Newfoundland. The broad coverage and consistency of the north-northeast ice flow indicates a possible ice divide, directly south of the study area along the height-of-land illustrated by Jenness (1960). Grant (1974) suggested a similiar ice divide arcing across the Island from the southwest to the east. Further evidence of an ice divide is provided by Proudfoot *et al.* (1988), who intrepreted the dominant ice flow in south-central Newfoundland to be south to southeast from


Northern Peninsula
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BAY OF EXPLOITS
Ice centre
Badger
Grand Falls
Mount Peyton
Gander Lake
BONAVISTA BAY
Red Indian Lake
Millertown
Ice centre
Terra Nova
Middle Ridge
Ice centre
Meelpaeg Lake

Figure 5. *Third ice-flow event.*

a source located in central Newfoundland. Although we cannot be certain that this southward flow coincided with the north-northeast flow in the north, there is only evidence for one ice-flow in the south so it is likely that they coincide.

THIRD ICE-FLOW EVENT

The third ice-flow event is to the northeast in the west of the field area and to the northwest in the east (Figure 5). This ice flow consistently crosscuts the earlier (second) north-northeast flow when observed on the same outcrop. Most of the previous workers did not separate this (the third) flow from the earlier (second) north-northeast ice flow, possibly because striation mapping was not their primary goal or because the area they investigated was not large enough. However, striations recorded by Hornbrook *et al.* (1975), Vanderveer and Taylor (1987) and Taylor and St. Croix (1989) do indicate two separate northward flows.

This third flow represents either two separate, but local ice-flow events or two contemporaneous ice flows across the area. Using Grant's (1974) theory of multiple shrinking ice caps, the north to northwest ice flow to the east of the Bay of Exploits may be related to a Middle Ridge ice centre, and to the west of the Bay of Exploits the northeastward ice flow may be related to an ice centre near Red Indian Lake.

FOURTH ICE-FLOW EVENT

A fourth and final ice flow in the region, was a relatively local, late phase event (Figure 6). This east-southeast-oriented ice flow was located south and west of the Bay of Exploits; and may be related to Grant's (1974) remnant ice centre in the Twin Ponds area north of Grand Falls. Similiar striations have also been mapped in the New Bay Pond area (Hornbrook *et al.*, 1975) and in the Grand Falls–Mount Peyton area (Taylor and St. Croix, 1989).

The final ice-flow event may be related to a cooling episode following initial deglaciation identified in north-central Newfoundland by Eyles (1977), Macpherson and Anderson (1985) and Liverman and St. Croix (1989b), which may have resulted in a readvance of remnent ice in the Springdale area (Liverman *et al.*, *this volume*).

TENTATIVE GLACIAL HISTORY

A tentative sequence of events in the deglaciation of north-central Newfoundland is postulated based on data collected during this survey and the work of others discussed above:

1) Coalescent ice caps were centred on the Northern Peninsula and central Newfoundland at the Late Wisconsinan maximum;

2) during the early stages of deglaciation these ice caps separated, permitting the central Newfoundland ice cap to flow from either an ice divide or an ice cap to some point past the modern coastline;

3) as deglaciation progressed, the central Newfoundland ice cap split into several independent ice caps producing their own ice flows; and

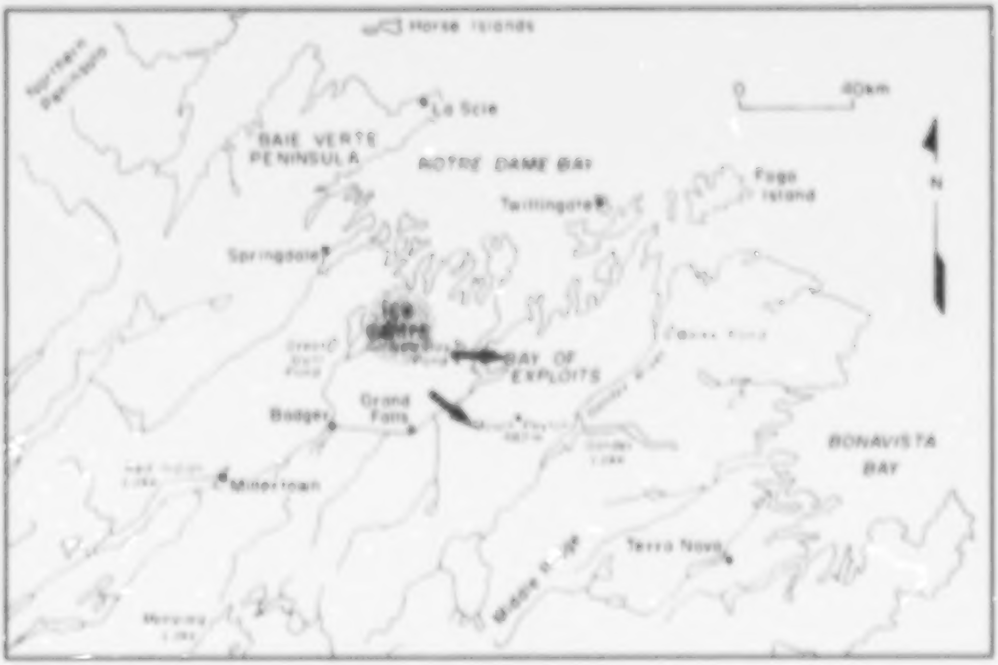

Figure 6. *Fourth ice-flow event.*

4) final decay of the central Newfoundland ice cap resulted in minor ice centres, which may have briefly readvanced, possibly as a result of cooling during the Younger Dryas.

IMPLICATIONS FOR DRIFT PROSPECTING

An understanding of the ice-flow history for this region will aid mineral exploration in interpreting the dispersion of mineralized float and geochemical anomalies in Quaternary sediments. In general, the most recent flow is responsible for the dispersion of mineralized source material (Batterson and Vatcher, *this volume;* Liverman and Scott, 1990). However, where multiple flows have been identified, dispersion by earlier flows should be considered (Proudfoot *et al.*, 1990). It is possible that the earlier east-southeast ice flow could initally have dispersed sediment that was subsequently reworked by the later north-northeast flows. Furthermore, most of the area has a thick drift cover (Liverman and Taylor, 1990) and it is possible that a complex till stratigraphy exists over parts of the region. In such cases, provenance and thus the geochemistry of each till sheet will differ, therefore, care must be taken in sampling.

CONCLUSION

This new ice-flow data from the Notre Dame Bay area, when combined with existing available data, adds to the comprehension of the glacial history of Newfoundland. Work being conducted in the offshore may substantiate whether ice from the Northern Peninsula did have an affect on the deglacial history of the Notre Dame Bay area. The model for deglaciation presented here will be tested over the coming field seasons by further mapping to check its validity.

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REFERENCES

Baird, D.M.
1950: Fogo Island map-area, Newfoundland. Geological Survey of Canada, Paper 50-22, 56 pages.

Batterson, M.J., St. Croix, L., Taylor, D.M. and Vatcher, S.
1991: Ice-flow indicators on the Gander Lake map sheet (NTS 2D/15). Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File 2D/15 (233), Map 91-01.

Batterson, M.J. and Vatcher, S.
This volume: Quaternary geology of the Gander (NTS 2D/15) map area.

Brookes, I.A.
1982: Ice marks in Newfoundland: a history of ideas. Geographie physique et Quaternaire, Volume XXXVI, No. 1-2, pages 139-163.

Eyles, N.
1977: Late Wisconsinan glacitectonic structures and evidence of postglacial permafrost in north-central Newfoundland. Canadian Journal of Earth Sciences, Volume 14, pages 2797-2806.

Grant, D.R.
1974: Prospecting in Newfoundland and the theory of multiple shrinking ice caps. Geological Survey of Canada, Paper 74-1B, pages 215-216.

1977: Glacial style and ice limits, the Quaternary stratigraphic record, and change of land and ocean level in the Atlantic Provinces, Canada. Geographie Physique et Quaternaire, Volume XXXI, pages 247-260.

1989: Quaternary geology of the Atlantic Appalachian region of Canada. *In* Quaternary Geology of Canada and Greenland. *Edited by* R.J. Fulton. Geological Survey of Canada, no. 1, pages 391-440, (*also in* Geological Society of America, The Geology of North America, V.K-1).

Hayes, J.J.
1951: Hodges Hill, Newfoundland. Geological Survey of Canada, Paper 51-5 (preliminary map).

Hornbrook, E.H.W., Davenport, P.H. and Grant, D.R.
1975: Regional and detailed geochemical exploration studies in glaciated terrain in Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 75-2, 116 pages.

Jenness, S.E.
1960: Late Pleistocene glaciation of eastern Newfoundland. Bulletin of the Geological Society of America, Volume 71, pages 161-180.

Liverman, D.G.E. and St. Croix, L.
1989a: Ice flow indicators on the Baie Verte Peninsula. (Parts NTS 12H, 12I, 2E); scale 1:100,000. Map 89-36.

1989b: Quaternary geology of the Baie Verte Peninsula. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 237-247.

Liverman, D.G.E. and Scott, S.
1990: Quaternary geology of the King's Point map sheet (NTS 12H/9). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 27-38.

Liverman, D.G.E., Scott, S. and Vatcher, H.
This volume: Quaternary geology of the Springdale map area (12H/8).

Liverman, D.G.E. and Taylor, D.M.
1990: Surfical geology of insular Newfoundland—preliminary version. Newfoundland Department of Mines and Energy, Geological Survey Branch, scale 1:500,000, Map 90-08.

Lundqvist, J.
1965: Glacial geology in northeastern Newfoundland. Geologiska Foreningens i Stockholm Forhandlingar, Volume 87, pages 285-306.

MacClintock, P. and Twenhofel, W.H.
1940: Wisconsin glaciation of Newfoundland. Bulletin of the Geological Society of America, Volume 51, pages 1729-1756.

Macpherson, J.B. and Anderson, T.W.
1985: Further evidence of late glacial climatic fluctuations from Newfoundland: pollen stratigraphy from a north coast site. *In* Current Research, Part B. Geological Survey of Canada, Paper 85-B, pages 383-390.

Murray, A.
1882: Glaciation of Newfoundland. Proceedings and transactions of the Royal Society of Canada, Volume 1, pages 55-76.

Paterson, W.S.B.
1981: The Physics of Glaciers—2nd Edition. Pergamon Press, New York. 380 pages.

Prest, V.K.
1970: Quaternary geology of Canada. *In* Geology and Economic Minerals of Canada. Geological Survey of Canada, Economic Geology, Report 1, pages 675-764.

Prest, V.K., Grant, D.R. and Rampton, V.N.
1968: Glacial map of Canada. Geological Survey of Canada, scale 1:5,000,000, Map 1253A.

Proudfoot, D.N., St. Croix, L., Scott, S., Taylor, D.M. and Vanderveer, D.G.
1988: Glacial striations in southeast central Newfoundland, scale 1:250,000. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File (NFLD 1725), Map 88-102.

Proudfoot, D.N., Scott, S., St. Croix, L. and Taylor, D.M.
1990: Quaternary geology of the Burnt Hill (NTS 2D/15)—Great Gull Lake (NTS 2D/6) map areas in southeast-central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 49-64.

Rogerson, R.J.
1982: The glaciation of Newfoundland and Labrador. *In* Prospecting in Areas of Glaciated Terrain. *Edited by* P.H. Davenport. Canadian Institute of Mining and Metallurgy, Geology Division Publication, pages, 37-56.

Sugden, D.E. and John, B.S.
1976: Glaciers and Landscape. Edward Arnold Ltd., London, England. 376 pages.

Taylor, D.M. and St. Croix, L.
1989: Glacial striations in north-central Newfoundland (parts of NTS 2D and 2E). Scale 1:250,000. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 89-108, Open File Nfld (1875).

1990: Ice-flow indicators in the Notre Dame Bay Area, Newfoundland (NTS 2E). Scale 1:250,000. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-126.

Tucker, C.M.
1976: Quaternary studies in Newfoundland: A short review. Maritime Sediments, Volume 12, No. 2, pages 61-73.

Vanderveer, D.G.
1983: Surfical and glacial geology reconnaissance survey of part of the Great Gull Pond map area (12H/1), Newfoundland. *In* Current Research. Department of Mines and Energy, Mineral Development Division, Report 83-1, pages 186-188.

1987: Landform classification maps for NTS areas 2E/8, 2F/4,5,6. Newfoundland Department of Mines and Energy, Mineral Development Division. Scale 1:50,000. Open File Nfld (1682).

Vanderveer, D.G. and Sparkes, B.G.
1980: Glacial-flow features–Red Indian Lake to Grand Falls. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File (NFLD 93), Map 80-20.

Vanderveer, D.G. and Taylor, D.M.
1987: Quaternary mapping in the Gander River area, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages, 39-43.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 69-78

SEDIMENTOLOGY OF QUATERNARY MARINE DEPOSITS IN THE SPRINGDALE–HALL'S BAY AREA

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ABSTRACT

The study area is located in the Springdale–Hall's Bay area of north-central Newfoundland. The origin and genesis of various waterlain sediments were studied in order to compile a history of sea-level changes for the area using a combination of sedimentological, paleontological, and geomorphological techniques.

Marine incursion, due to isostatic depression, was extensive throughout the Indian Brook and South Brook valleys, reaching at least 10 km inland. Marine clay in three sections was deposited under calm conditions, distal to the sediment source, as indicated by the absence of poorly sorted coarse material. Dropstones, indicative of ice rafting, were found in the clay. The clays were deposited by a combination of suspension settling and sediment-gravity flows. The sediment geochemical results suggest a brackish-marine environment. Shells of Mya arenaria, Balanus hameri, Macoma balthica, *and* Hiatella arctica *found in the clays, also indicate a similar brackish-water depositional environment.*

Sea-level history deduced from this study indicates that ice-contact deltas were formed and that a series of successively lower terraces (indicating isostatic rebound) are also present. Deltaic sequences with surfaces ranging from 14 to 75 m above the present sea level were a result of higher sea-level stands. Most of the deltaic sediments were formed as ice-contact fan-deltas, but two sites are interpreted as ice-distal fans. Terraces in this study indicate that ice-contact deltas were formed at elevations of 75, 72, 64, 51, 50, 30, 20, and 13 m above sea level.

Slope stability may represent a problem along Indian Brook, due to the presence of clays. The extent of clay, up to 10 km inland and up to 30 m thick, suggests it may be an economic resource for brickmaking or pottery. The large amounts of permeable sands and gravels in the area make the location of waste-disposal sites difficult.

INTRODUCTION

The study area is located in the Springdale–Hall's Bay area of Newfoundland, lying between 56°15'W and 56°00'W and 49°32'N and 49°20'N (part of NTS 12H/8 and 12H/9) (Figure 1). Following the Late Wisconsinan deglaciation of this area, raised sea levels, due to isostatic depression, resulted in marine inundation of areas lying below 75 m, above the present sea level (Tucker, 1973). As a result of subsequent isostatic rebound, raised-marine deposits occur along the shores of Hall's Bay and these marine and coastal sediments can be easily investigated. The objectives of the study are:

1) to describe fine-grained rhythmically bedded material and related sediments, in order to determine their origin and modes of genesis;

2) to describe the fossil assemblages present;

3) to study the geomorphology of the area; and

4) to integrate the sedimentology, paleontology, and geomorphology to determine the history of sea-level changes.

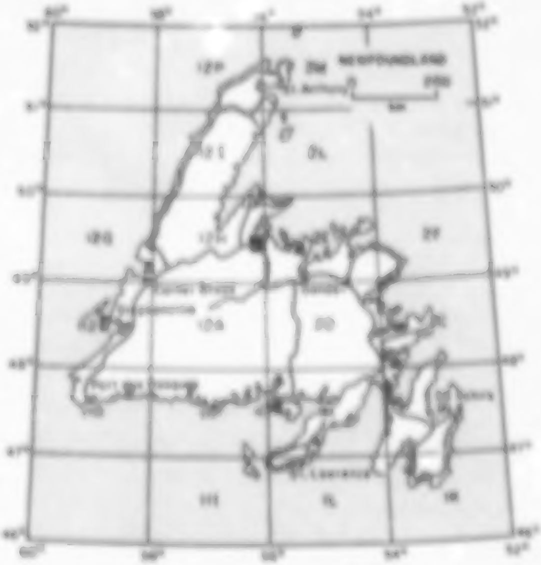

Figure 1. *Location map of study area.*

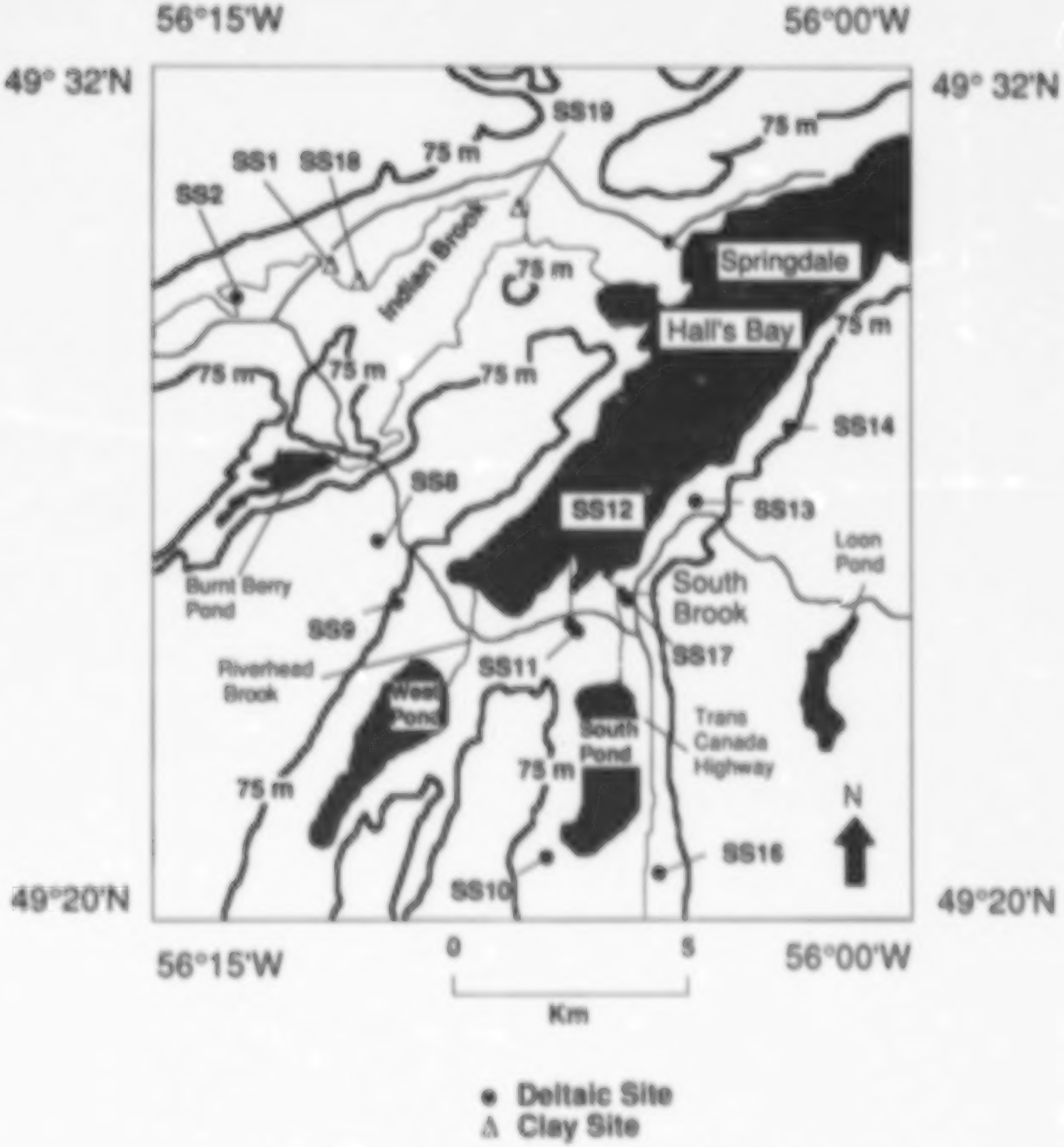
56°15'W
56°00'W
49° 32'N
49° 32'N
SS19
75 m
SS1
SS18
SS2
Indian Brook
75 m
Springdale
Hall's Bay
75 m
75 m
75 m
75 m
SS14
SS8
SS12
SS13
Loon Pond
Burnt Berry Pond
South Brook
SS9
Riverhead Brook
SS11
SS17
West Pond
South Pond
Trans Canada Highway
75 m
75 m
N
SS16
SS10
49°20'N
49°20'N
56°15'W
0
5
Km
56°00'W
● Deltaic Site
Δ Clay Site

Figure 2. *Location of features and sections named in the text.*

Three sections consisting dominantly of clay and silt along Indian Brook were examined, as well as ten sections situated over the remainder of the study area.

PHYSIOGRAPHY

The study area includes Hall's Bay, South Brook, Springdale and Indian Pond Park. The major river in the area is Indian Brook and other rivers include Burnt Berry Brook, Riverhead Brook, and South Brook (Figure 2). Lakes are common and include South Pond, West Pond, Burnt Berry Pond and Loon Pond. Approximately 40 percent of the area lies below the 75 m contour.

PREVIOUS WORK

Richards (1940) identified two shells found by MacClintock and Twenhofel (1940), from red marine silts at

Springdale (Pelecypoda *Saxicava arctica* Linné and Crustacea *Balanus crenatus* Bruguière). These species indicate a brackish-, probably shallow-water environment. MacClintock and Twenhofel (1940) briefly described large deltas at 75 m above sea level (a.s.l.) at Springdale and South Brook and interpreted them as outwash from glaciers draining into Hall's Bay. Jenness (1960) believed that these deltas were contemporaneous, interpreted them as glaciolacustrine features, and used their levels to construct an isobase system. Lundqvist (1965) accepted Jenness's glaciolacustrine origin for the deltas due to the presence of varved clays in the Indian Brook valley and also because the deltas were far above the highest marine limit. The western part of the delta at Springdale contain beds dipping to the east, which were believed to indicate sediment transport from ice in the Indian Brook Valley. Lundqvist (1965) believed the delta at South Brook valley was deposited in front of an ice tongue, as the existence of such a lobe was demonstrated by several lateral drainage channels on the southern side of West Pond.

A sample of *Balanus* sp., found by Grant (1974) in a terrace located at the head of Hall's Bay, was ^{14}C dated at 12000 ± 220 years BP (GSC−1733). This date was interpreted to represent the time of formation of the 75 m a.s.l. glaciomarine deltas on the northeast coast of Newfoundland. A ^{14}C date of 11,000 ± 190 years BP (GSC−2085; Lowdon and Blake, 1975) on shells (*Mytilus edulis* and *Hiatella arctica*) found in gravels interpreted as delta bottomsets, near South Brook (Tucker, 1973), is also interpreted to date the glaciomarine deltas.

Tucker (1974) identified five marine terraces at 66, 60, 54, 15, and 9 m a.s.l., which formed as a result of isostatic rebound and suggested that the postglacial emergence has been 75 m. He interpreted that the calving of an ice front rapidly deglaciated Hall's Bay, until the ice became landfast in Indian Brook and in areas to the south. It remained in this position as the deltas were being deposited.

Tucker (1973) described silt and sand rhythmites in the Springdale area but was unable to determine if they were marine or lacustrine in origin. Vanderveer (1977) described a clay deposit, located east of the bridge over Indian Brook near Springdale, as a varved sequence containing some lenses of silt and sand, which was overlain by sand and gravel (the clay was identified as a potential economic resource for the manufacture of red brick and possibly studio products). Grant (1986) published surficial maps for the NTS 12H/8 and 12H/9 map areas, which showed sand and gravel deltas around Hall's Bay.

In 1987, the Newfoundland Department of Environment and Lands drilled a groundwater well at Indian River Provincial Park. Samples showed sands and gravels down to 2 m and clay from 2 to 2.5 m depth. Samples were not taken between 2.5 and 22 m. Sands and gravels were present at 22 m; clay at 23 m, and additional sands and gravels at 27.4 m depth. Liverman and Scott (1990) briefly described the exposures east of the bridge over Indian Brook as consisting of a well-sorted, laminated and bedded silt and clay unit up to 10 m thick. The deposit was interpreted to represent an ice-distal glaciomarine environment. Surficial mapping of the 12H/8 map area was undertaken in conjunction with this project (see Liverman *et al.*, *this volume*).

ACCESS AND FIELD METHODS

Access to the area is good, except for the area south of Indian Brook and east of the Springdale highway. Selected exposures were located and examined, and detailed descriptions recorded. Description was supplemented by sampling for textural and geochemical analysis. In addition, several samples were taken at each site for microfossil analysis. Shells found at some sections were described, identified, and have been submitted for ^{14}C dating. Box cores were taken from section SS1 (Figure 2), dried, and will be examined in detail at a later date. The orientations of all paleocurrent indicators were measured using a Brunton compass. An altimeter was used to measure the elevation of the tops of sections, with compensation for drift being made by recording the time of the reading at each location and subsequently returning to a known altitude. The resulting elevations are accurate to ± 5 m.

SEDIMENTOLOGY

Ten sections indicating deltaic deposition at higher than present sea levels were located; three sections containing clay units were also found. These exposures are described and interpreted below. The locations of these sections are shown on Figure 2.

DELTAIC SECTIONS

Of the ten sections showing deltaic features, (Table 1), sections SS2 (68 m), SS8 (72 m), SS9 (20 m), SS10 (50 m), SS11 (64 m), SS12 (64 m), and SS16 (51 m) consist of interbedded, poorly sorted, sands and gravels having some beds dipping 10 to 26° north or north-northeast. Sections SS13 (74 m), SS14 (72 m), and SS17 (13 m) also consist of interbedded poorly sorted sands and gravels, but these are generally better sorted and finer grained than the seven sections mentioned earlier. This distinction, along with the geomorphological setting, is sufficient to classify them as a separate group for discussion.

The first seven sections mentioned are, in general, composed of interbedded sands and gravels. The sand beds consist of well-sorted fine to medium sand, 5 to 50 cm thick, and contain less than 10 percent sub-angular to sub-rounded pebbles ranging from 1 to 5 cm in diameter. The sand beds are usually structureless, but some show a few fining or coarsening upward sequences and ripples. The gravel beds are poorly sorted, 5 to 50 cm thick, having sub-angular to sub-rounded pebbles and cobbles with long axes of 3 to 30 cm. The beds are generally structureless, and both sharp and gradational contacts are present.

Section SS12, at an elevation of 64 m, consists of interbedded, poorly sorted sands and gravels. This section is divided into three units. Unit 1 has beds, 1 to 70 cm thick,

Table 1. Deltaic section data and sedimentological interpretation

Section Number	Latitude and Longitude	Maximum Thickness of Exposure	Elevation of Surface	Comments
SS2	56°13'30" 49°29'02"	15 m	68 m	Rapid water flow, constructing a delta into a raised post glacial sea
SS8	59°08'20" 49°25'56"	2.1 m	72 m	Upper part of deltaic sequence
SS9	56°08'35" 49°25'10"	75 m	20 m	Detalic sediments studied by Tucker (1974)
SS10	56°08'56" 49°21'02"	2.3 m	50 m	Upper part of deltaic sequence
SS11 and SS12	56°06'40" 49°25'20" and 56°06'50" 49°25'25"	20 m	64 m	Deltaic, with top parts of the sequences showing braided channel characteristics
SS16	56°05'33" 49°21'00"	6.5 m	51 m	Upper part of deltaic sequence
SS17	56°04'41" 49°25'40"	5 m	13 m	Well-sorted sediment indicates distal location for the lower part of the complex
SS13	56°03'30" 49°26'40"	10 m	74 m	Ice-distal fan delta, slightly below wave base
SS14	56°02'30" 49°27'15"	10 m	72 m	Ice-contact fan delta, with braided channels

of structureless fine to coarse sand with less than 2 percent sub-angular to sub-rounded pebbles 1 to 3 cm in diameter. Some beds contain fining upward sequences. All the beds dip 18° north. At the base of 5 percent of the beds, there are pebble stringers containing pebbles 0.5 to 1 cm in diameter and are sub-angular to sub-rounded. The upper part of this unit contains an upwardly increasing number of medium pebbly sand beds with 45 percent sub-rounded to well-rounded pebbles, 0.5 to 8 cm in diameter.

Unit 2 consists of 10- to 70-cm-thick, well-sorted, fine- to coarse-sand beds. The beds dip from 26° in the northern part of the section to 18° in the southern parts. Many beds contain no large clasts, whereas others have less than 4 percent sub-rounded to rounded pebbles, 1 to 2 cm in diameter. Beds dip 18° north, with some pinching out laterally, and both the upper and lower contacts are sharp. Concave-convex channel cuts are visible at the base of this unit. Climbing ripples are present with an average wavelength and amplitude of 1.5 and 15 cm, respectively; the ripples indicate flow to the north.

Unit 3 consists of 2 m of poorly sorted, flat-lying, sand and gravel beds (20 cm to 1 m thick), with approximately 50 percent sub-angular to sub-rounded pebbles and cobbles, 0.5 to 12 cm in diameter. These beds truncate the underlying dipping beds.

Site SS16, at an elevation of 51 m, is perhaps more typical of the seven deltaic sites mentioned earlier. It is comprised of 15-cm to 1-m-thick interbedded, well-sorted, fine sand and pebbly sand beds that dip 22° north-northwest. The fine sand beds are mostly structureless except at the base of the section where some beds show horizontal laminations of 1 to 5 cm associated with fining upward sequences. Some of these fine sand beds contain plano-convex sand lenses with less than 2 percent medium to coarse pebbles. The pebbles in these lenses are sub-angular and range in diameter from 1 to 3 cm. Normal epigenetic faulting is visible in some sand beds. The pebbly sand beds range in thickness from 5 to 50 cm and consist of moderately sorted pebble sand containing sub-angular to sub-rounded clasts, 1 to 6 cm in diameter. Contacts are sharp and the beds are sometimes structureless whereas at other places they coarsen upward. Some beds also contain irregular shaped lenses, 1 to 3 cm thick and made of coarser, pebbly sand.

The three sections SS13 (74 m), SS14 (72 m), and SS17 (13 m), which generally have better-sorted and fine-grained sediment are treated as a group and are discussed separately. Sections SS13 and SS14 consist of interbedded sands and gravels, but SS13 contains fewer beds of coarse gravel than the other deltaic sequences from the earlier discussed sections. Beds at SS13 and SS14 range in thickness from 5 to 100 cm and dip 24 to 26° north. Both sections have trough crossbedding in gravels, soft sediment clasts, ripples and sub-rounded to rounded pebbles to cobbles, 1 to 50 cm in diameter. Although some beds are well sorted and rippled, in general, the sediments are poorly sorted and structureless. Contacts between beds are generally sharp.

Section SS13 is divided into three units (Plate 1). Unit 1 consists of 6.4 m of well-sorted, medium to fine sand beds, structureless interbedded pebbly sands, and granule gravel strata. Contacts range from gradational to sharp between sand beds. Within the sand beds, at the base of this unit, are convexo-concave lenses, 1.5 cm by 2 cm, of fine sand and silt that fines upward. There is less than 2 percent sub-angular to sub-rounded pebbles in the sand beds. The granule gravel beds are poorly sorted, range in thickness from 8 to 18 cm, and dip 28° north. The pebbly sands are moderately sorted and range from 5 to 10 cm thick, with sub-angular pebbles 1 to 6 cm in diameter. These units have pebble imbrication indicating flow to the northwest, and some show fining upward sequences to open worked gravel.

Unit 2 consists of 3.8 m of fine sand beds with silt and clay drapes and interbeds of granule–gravel. The beds dip 24° to the northwest and are commonly laterally discontinuous. This unit has rippled beds in the upper 1.5 m. The sand beds show some fining upward sequences, contain less than 1 percent pebbles, and contain ripples indicating flow to the north or northeast with an average amplitude and wavelength of 2.5 cm and 9 cm, respectively. The granule–gravel beds are 5 to 70 cm thick, moderately sorted, and structureless. Contacts between all beds are sharp. Some of the sand beds in this unit contain syngenetic reverse faults with displacements of 1 to 4 mm at an angle of 25° that do not continue into the overlying sediments.

Plate 1. *Deltaic section SS13.*

Unit 3 is comprised of 80 cm, flat-lying to channelized, pebble granule gravel interbedded with fine sand. The beds are well-sorted and contain some silt and clay laminae. The basal contact is sharp, truncating the dipping beds in Unit 2.

INTERPRETATION AND IMPLICATIONS FOR SEA-LEVEL HISTORY

Most of the deltaic sediments were deposited in contact with glacial ice, as indicated by the coarse clasts and poor sorting of the sediment (see Reading, 1978). The ice front is believed to have been at 75 m a.s.l. along the west side of Hall's Bay, but to the east, ice is believed to have been farther inland from the coast, as demonstrated by the expanses of gravel extending 1 to 2 km southward from sections SS13 and SS14.

The climbing ripple drift crosslaminations present in Unit 2, at section SS12, were oriented indicating flow to the northeast and are interpreted as depositional stoss features (type B of Jopling and Walker, 1969). These features develop where sediment loads exceed the transport capacity of flow, and where flow velocities are low (Stanley, 1974; Ashley *et al.*, 1982). Development of climbing ripples requires rapid, periodic sediment accumulation, and is common in glaciofluvial sequences marked by seasonal fluctuation in flow discharge and velocity. Fining upward sequences common within the ripple drift indicate successively increasing suspended load/bedload ratios, as flow velocity declined during each discreet accumulation event. The combination of sediment grain-size, orientation of ripples, the dip of the beds, and the elevation of 64 m allows the interpretation of this section to be a deltaic sequence, showing braided channel characteristics.

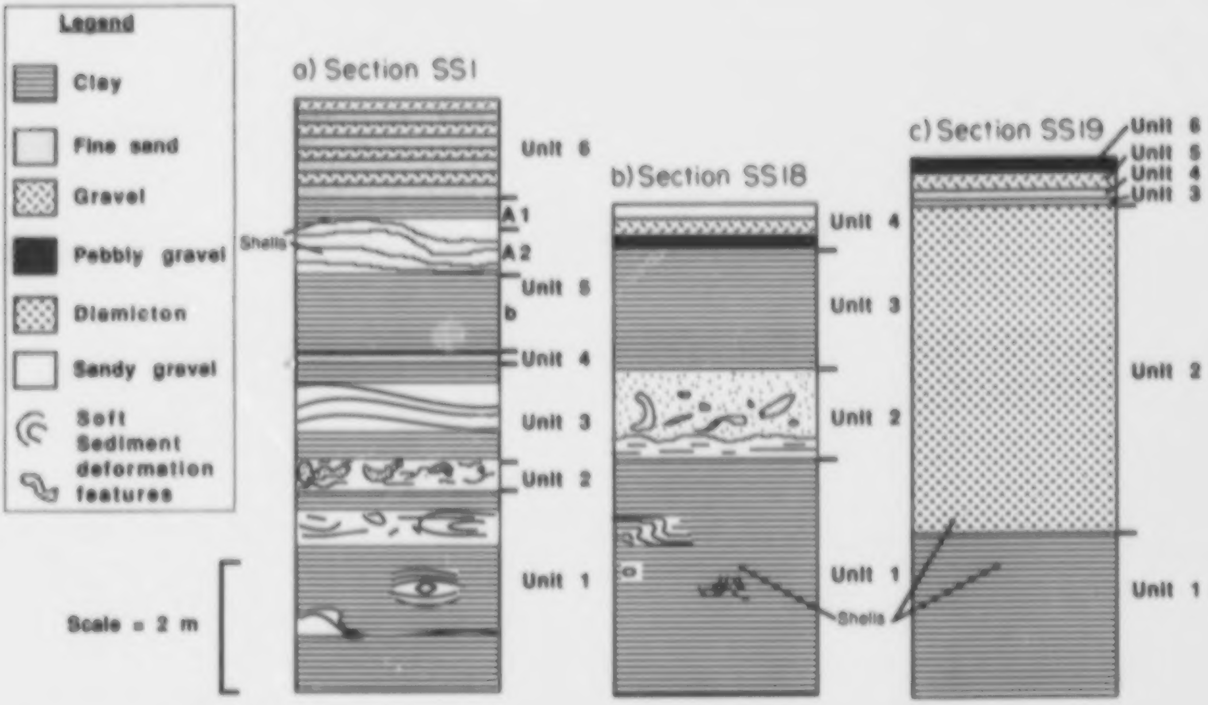

Figure 3. *a) Sedimentary column of SS1, b) sedimentary column of SS18, c) sedimentary column of SS19.*

Section SS16 (51 m) is interpreted to be the upper part of a deltaic sequence. Tucker (1974) identified deltas and terraces at 66, 60, and 54 m a.s.l. The delta surfaces of SS10 and SS16 at 50 m a.s.l. located south of South Pond maybe chronologically equivalent to the 54 m terraces at Springdale, Burnt Berry Brook, and West Pond, identified by Tucker (1974); in any event, they indicate a major sea-level stand.

At section SS13, the syngenetic reverse faulting in Unit 2 suggests loading of the sediment, possibly by flows. Ripples in Unit 2 indicate current flow to the north-northwest. The open-worked granule–gravel may be grain-flow sediments, and the presence of pebbles in silt and clay material suggests ice rafting. The overall assemblage can be interpreted as an underflow fan deposit distal to the source. The presence of fine beds, the intertonguing of beds, their lateral discontinuity, and the dip of the beds suggest a distal, deltaic origin for the section. Thus, the sediments formed as an ice-distal fan-delta located just below wave base.

The conclusion drawn is that when the ice stood at 75 m, deltaic deposits were formed near West Pond, but on the east side of Hall's Bay, the ice was at least 2 km south of the coast. This is interpreted from the sediments deposited at sections SS13, SS14, and SS17, all of which appear to have characteristics indicating an ice-distal deltaic origin. The other seven deltaic sections have characteristics indicating ice-contact formation. The differing elevations indicate many were formed at different times but all seven indicate a proximity to the source of the sediment.

CLAY SECTIONS

Three rhythmically bedded sections were found along Indian Brook. These were examined in order to determine the limit of marine transgression.

Section SS1

This section of rhythmically bedded silt, clay, and sand, is located adjacent to the bridge over Indian Brook along Springdale Road at an altitude of 30 m a.s.l.. It is 8.9 m thick and extends for 20 m. The section is divided into six units (Figure 3a). The strata dips at 1 to 10° east.

Unit 1 consists of a minimum of 3.02 m of laminated silt and clay along with some fine sand laminae and beds. These strata have sharp upper and lower contacts and are mostly internally structureless. There are some normally graded sand laminae in the unit. The unit contains rare coarse clasts ranging from 1 to 10 cm in diameter that deform underlying strata and are draped by the overlying strata (Plate 2).

Water-escape and deformation structures consisting of beds or laminae, which are broken apart and pushed up into the overlying strata or folded and pinched out, are present (Plate 3). Several of these structures have eroded tops on the folds, indicating erosional contacts of the laminae and beds. Laminae of clay and silt alternate between reddish brown (2.5YR 5/4) and yellowish brown (10YR 5/4), when moist.

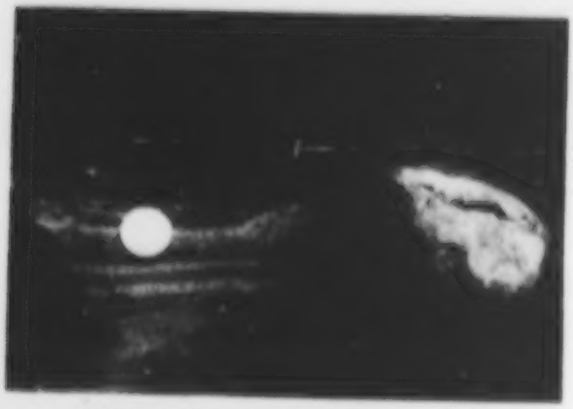

Plate 2. *Dropstone in sediment at SSI.*

Plate 3. *Deformation in sediment at SSI.*

Unit 2 ranges from 5 to 46 cm thick and is composed of deformed sand and clay. Locally derived sub-angular to sub-rounded granites and felsic volcanic pebbles ranging from 1 to 2 cm in diameter are common. The upper contact of the unit is sharp and erosional (truncating deformation features). The orientations of fold axes indicate deformation caused by flow to the northeast. The unit pinches out to the east over 15 m.

Unit 3 is 1.5 m thick and consists of alternating red and green silt, sand and clay laminae ranging from 1 to 5 mm thick. At the base of the unit, these laminae are flat-lying with sharp upper and lower contacts and are 1 to 2 mm thick. In the upper part of the unit, laminae are folded, distorted and appear convoluted. The unit is not laterally extensive. Fold-axis measurements (analyzed using the techniques of Woodcock, 1979) indicate that deformation was produced by flow to the northeast.

Unit 4 is 0.15 to 0.40 cm thick and is composed of a laminated silty diamicton. Approximately 5 percent sub-angular pebbles are present. Some intraclasts (1 to 2 cm) of clay are present and fold-axis measurements indicate a flow to the northeast. Both the upper and lower contacts are sharp.

Unit 5 is composed of 2.3 m of laminated silt and clay associated with some pebbles. These strata are internally structureless and have less than 1 percent pebbles scattered throughout. The pebbles deform underlying strata and are draped by overlying strata. Minor slumping and water-escape structures such as sags, dish structures and load-casts are found and the upper contact of the unit is sharp and erosional.

Shells were located at two elevations in Unit 5 at 27.4 and 28.5 m. These articulated *Mya arenaria* shells are in growth position. The shells range from 0.8 to 1.4 cm long and were extremely friable. They have been submitted for accelerator ^{14}C dating. *Mya arenaria* inhabits brackish-marine environments (Wagner, 1970).

Unit 6 consists of 1.47 m of interbedded sand and gravel. These beds are structureless and range from 10 to 40 cm thick. The sand is medium to coarse grained and well-sorted. Gravel beds have clasts ranging from 1 to 5 cm in diameter and are well-sorted. The unit is erosionally truncated at the upper surface of the exposure.

Section SSI8

Site SSI8 is located about 0.5 km east of SSI, on the north side of Indian Brook, at an altitude of 30 m (Figure 3b). This section has 8 m of exposure and is divided into four units.

Unit 1 is a minimum of 3 m thick and consists of laminated sand, silt, and clay beds ranging from 1 mm to 40 cm thick, and containing less than 1 percent sub-angular to sub-rounded pebbles. When moist, the clay has alternating colours of weak red (10R 5/2) and light brownish-grey (2.5Y 6/2). There are rare coarse clasts present, which deform the underlying strata, and which are draped by the overlying beds. Water-escape structures are present in some laminae. Minor normal faults of 2 cm displacement are syndepositional in origin, as the upper parts of the faults are draped and do not persist in the overlying strata. All contacts were sharp. Shells were found in Unit 1 at 24.3 m. They were fragmented and may have been reworked. These shell fragments have been identified as bivalves, possibly *Mya arenaria*, but their poor preservation limits the confidence of the identification. The shells have been submitted for ^{14}C dating.

Unit 2 is 1.25 m thick and is composed of laminated silt, clay, and sand at the base, grading up into a well-sorted, fine sand. The basal laminae are flat-lying silt and clay, with rare sand laminae. The upper part of the unit is interbedded, convoluted, and folded sand, silt, and clay. Some granules and intraclasts (1 to 2 cm in diameter and composed of clay) are present in the sand. Fold-nose measurements and a 1 to 10° dip in the beds indicate an easterly deformation direction. The unit thins to the west and east; contacts between laminae are sharp.

Unit 3 consists of 1.87 m of laminated silt and clay and well-sorted (fine to medium) sand. The clay laminae make up 80 percent of the unit. The basal contact is sharp whereas the upper contact is gradational. Unit 4 consists 1.4 m of planar-bedded, poorly sorted pebbly gravel and pebbly sand. The pebbles are sub-rounded and 1 to 6 cm in size. The beds range in thickness from 10 to 40 cm.

Section SS19

Site SS19 is located on the south side of Indian Brook, at the falls, in the George Huxter Memorial Park near Springdale. Brief reconnaissance of this section shows that it is 19.9 m a.s.l. and consists of six units (Figure 3c).

Unit 1 is composed of 2.5 m of laminated silt and clay having sharp contacts between laminae. These alternate red and green laminae range from 1 to 2 mm thick (similar to those of sections SS1 and SS18; bivalve shells were located at 12.9 m, Unit 2, and at 12.45 m, Unit 1; Plate 4). Four different species were found: *Mya truncata Linne; Hiatella arctica; Macoma balthica;* and *Balanus hameri* (barnacles). Some of these shells were in growth position, whereas others were fragmented. The barnacle fossils were abundant in the lower 50 cm of Unit 2 and cobbles within the sediment had barnacle shells still attached to them. These species are indicative of cold, shallow (5.5 m) to deep (183 m) water. They are also believed to be indicative of a wide range of salinities (Wagner, 1970). The shells located here have been submitted for ^{14}C dating. The upper contact is gradational with Unit 2.

Plate 4. *Shell (*Mya truncata*) at section SS19. Shell is 2.8 cm by 4.5 cm in size.*

Unit 2 consists of a coarse to medium sand containing approximately 45 percent sub-angular to sub-rounded pebbles to cobbles 0.5 to 25 cm in diameter. The basal 65 cm of the unit has a high clay and shell content and is very compact. The upper part of the unit has less clay and the material is loose; the upper contact is sharp.

Unit 3 is 15 cm of massive diamicton consisting of a sandy silt matrix containing approximately 55 percent pebbles to boulders. The pebbles and boulders range from 1 to 70 cm in diameter; the upper contact is gradational.

Unit 4 consists of 20 cm of massive, poorly sorted medium sand continaing a few sub-angular to sub-rounded pebbles. The upper contact is sharp with Unit 5, which consists of 50 cm of a massive clast supported pebble gravel. Unit 6 has a lower gradational contact and consists of 30 cm of massive pebbly medium sand.

GEOCHEMISTRY

Geochemical data, in particular the concentration of boron and vanadium, can be interpreted to indicate the paleosalinity of the depositional environment (Shimp *et al.*, 1969). The results of preliminary vanadium analyses are shown in Table 2 and the paleosalinity of the depositional environment of the clays has been inferred on the basis of the vanadium content. From a study by Catto *et al.* (1981) done in the Ottawa valley, it was determined that vanadium concentrations in excess of 115 ppm indicate a marine depositional environment, whereas concentrations lower than 60 ppm indicate a freshwater environment. Thus, it can be deduced that all the samples tested for the Springdale area, which range between 84 and 109 ppm, fall within the range indicating brackish environments. The application of Catto *et al.'s* (1981) results to this area, is speculative, in the absence of data allowing the effect of background vanadium concentrations to be evaluated.

INTERPRETATION AND DISCUSSION

The three well-exposed, rhythmically bedded clay sections located along Indian Brook appear to have had similar depositional environments and modes of origin.

At section SS1, Units 1, 3, and 5, consisting of laminated, well-sorted silt and clay, suggest deposition by settling of sediment from suspension. Section SS18 Units 1 and 3, also laminated silt and clay, appear to have formed in the same way as those above. The same holds true for Unit 1 at section SS19. The well-sorted, fine-grained nature, lack of coarse debris, and lack of current indicators suggest suspension settling for these units. The rhythmically laminated silts and clays contain fine sand laminae in them. These laminae, due to their coarser nature may have formed by small sediment flows downslope. All of these units appear to have about 10 percent soft-sediment deformation structures in the form of sag and drop, convolute laminations, loading, and dish structures. The sand laminae cause load-casts and other water-escape structures in these units. The units discussed here all contain coarse clasts that deform the strata. These may be dropstones from floating ice as were described by Thomas and Connell (1985).

At section SS1, Units 2 and 4, consisting of convoluted laminated sand and silty clay, suggest periods of current flow, allowing the deposition of these sand strata. Section SS18, Unit 2, is believed to be the same as the units described above. A variety of soft-sediment deformation features are present in these units. The ones identified here include gravitationally unstable features such as water-escape structures, convolute laminations, load-casts, and ball-and-pillow structures. These

Table 2. Vanadium concentrations in clay deposits

Section Number	Sample Number	Unit Number	Vanadium ppm
SS1	90003	unit 1 base	99
SS1	90014	unit 1 top	95
SS1	90024	unit 3	109
SS1	90031	unit 6b top	109
SS1	90036	unit 6a2	106
SS18	90045	unit 1 middle	92
SS18	90052	unit 1 throughout	84
SS18	90059	unit 3	103
SS19	90069	unit 1	106

were identified as similar to those described by Allen (1984). Allen (1984) suggests that these features reflect the early consolidation history more so than the depositional environment, but the depositional environment controls the consolidation history. He further states that such features are typical of waterlain sediments and arise where high sedimentation rates prevail to promote loose packing of sands and silts. It is possible that the units here are turbidites, hence, they represent both suspended settling and flow.

Paleoflow measurements made on fold axes indicate flow to the northeast and east in sections SS1 and SS18, respectively. No such measurements were made on section SS19. Preliminary geochemical evidence from all these units suggest a brackish environment at the time of their formation.

An interpretation of these sequences in section SS1 and section SS18, on a regional level, involves the following sequence of events. Initial calm suspension settling of clays, along with periodic influxes of fine sand from minor current flows. This is followed by low-density debris flows or turbidites, which deposited coarser, moderately sorted sandy units associated with minor slumping. Deposition then reverts to suspension settling again and finally concludes with a capping gravel deposit of outwash or stream origin. The preliminary interpretation at section SS19 is restricted to Units 1, 2 and 6. The result is a sequence wherein Unit 1 represents suspension settling, Unit 2 is possibly a debris-flow deposit, and Unit 6 is a gravel cap that may be fluvial or beach sediments.

SUMMARY AND CONCLUSIONS

The clay deposits described here indicate a brackish-marine environment, marked by downslope sediment movement and represent marine incursion up to 10 km inland. Sedimentologically, the clays were deposited by suspension settling and sediment-gravity flows. The sea-level chronology cannot be reconstructed until dates on the shells are received.

The deltaic sections also indicate a progressive lowering of sea level since deglaciation. Geomorphological and sedimentological data indicate that the ice front stood at the mouth of West Brook and South Brook and bordered Hall's Bay but was 1 to 2 km south of sections SS13 and SS14. Subsequently, the ice retreated south through South Pond, and marine deposits and terraces indicate that inundation was at 50 m a.s.l..

The marine clays pose slope-stability problems along Indian Brook, which should be taken into consideration in any construction (Plate 5). The clays may form an economic resource (Vanderveer, 1977).

Plate 5. *Modern slumping along Indian Brook.*

This work indicates that there is a substantial volume of marine sediment present. Due to the large amounts of sands and gravels in the marine deltas, care must be taken in planning the location of municipal dump sites due to seepage of the material. However, these sands and gravels are good sources of aggregate.

FURTHER WORK

The sediment descriptions will aid development of a model for glaciomarine sedimentation in this area. It is hoped that chronological data for sea-level changes, together with sedimentological analyses, will enable correlation with offshore sedimentary assemblages. Analysis and interpretation of data for this area will continue.

ACKNOWLEDGMENTS

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REFERENCES

Allen, J.R.L.
1984: Developments in Sedimentology. Sedimentary structures, their character and physical basis. Elsevier, 663 pages.

Ashley, G.M., Southard, J.B. and Boothroyd, J.C.
1982: Deposition of climbing-ripple beds: a flume simulation. Sedimentology, Volume 29, pages 67-79.

Catto, N.R., Patterson, R.J. and Gorman, W.A.
1981: Late Quaternary marine sediments at Chalk River, Ontario. Canadian Journal of Earth Sciences, Volume 18, pages 1261-1267.

Grant D.R.
1974: Terrain studies of Cape Breton Island, Nova Scotia and the Northern Peninsula, Newfoundland. *In* Report of Activities, Part A. Geological Survey of Canada, Paper 74-1A, pages 241-246.

1986: Surficial geology of the King's Point and Springdale 1:50,000 map sheets. Geological Survey of Canada, Open File Map 1312.

Jopling, A.V. and Walker, R.G.
1969: Morphology and origin of ripple-drift cross laminations, with examples from the Pleistocene of Massachusetts. Journal of Sedimentary Petrology, Volume 38, pages 971-984.

Liverman, D.G.E. and Scott, S.
1990: Quaternary geology of the King's Point map sheet (NTS 12H/9). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 27-38.

Liverman, D.G.E., Scott, S. and Vatcher, H.
This volume: Quaternary geology of the Springdale map area (12H/8).

Lowden, J.A. and Blake, Jr. W.
1975: Geological Survey of Canada radiocarbon dates XV. Report 75-7, 32 pages.

Lundqvist, J.
1965: Glacial geology in northeastern Newfoundland. Geologiska Foreningens i Stockholm Forhandlingar, Volume 87, pages 285-306.

MacClintock, P. and Twenhofel, W.H.
1940: Wisconsin glaciation of Newfoundland. Geological Society of America Bulletin, Volume 51, pages 1729-1756.

Reading, H.G.
1978: Sedimentary Environments and Facies. Elsevier, New York, 557 pages.

Richards, H.G.
1940: Marine pleistocene fossils from Newfoundland. Geological Society of America Bulletin, Volume 51, pages 1781-1788.

Shimp, N.F., Witters, J., Potter, P.E. and Schleicher, J.A.
1969: Distinguishing marine and fresh water muds. Journal of Geology, Volume 77, pages 566-580.

Stanley, K.O.
1974: Morphology and hydraulic significance of climbing ripples with superimposed micro-ripple-drift cross-lamination in lower quaternary lake silts, Nebraska. Journal of Sedimentary Petrology, Volume 44, pages 472-483.

Thomas, G.S.P. and Connell, R.J.
1985: Iceberg drop, dump, and grounding structures from Pleistocene glacio-lacustrine sediments, Scotland. Journal of Sedimentary Petrology, Volume 55, pages 243-249.

Tucker, C.M.
1973: The glacial geomorphology of west-central Newfoundland; Halls Bay to Topsails. Unpublished M.Sc. thesis, Department of Geography, Memorial University of Newfoundland, St. John's, 132 pages.

1974: A series of raised Pleistocene deltas in Hall's Bay, Newfoundland. Maritime Sediments, Volume 10, pages 1-7.

Vanderveer, D.G.
1977: Clay deposits of Newfoundland and Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-9, 41 pages.

Wagner, F.J.E.
1970: Faunas of the Pleistocene Champlain Sea. Geological Survey of Canada, Bulletin 181, 104 pages.

Woodcock, N.H.
1979: The use of structures as palaeoslope orientation estimators. Sedimentology, Volume 26, pages 83-99.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 79-82

A NEW FOSSIL LOCALITY IN THE BAY OF EXPLOITS, CENTRAL NEWFOUNDLAND

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ABSTRACT

A previously unrecorded shelly fauna was recovered from limestone lenses and layers in turbidite deposits of the Botwood Group exposed on Upper Black Island. The fauna is dominated by cyclopygid trilobites indicative of a probable Late Ordovician, Ashgill (Rawtheyan) age.

INTRODUCTION

A previously unrecorded shelly fauna was recovered from limestone lenses and layers in apparently slumped turbidite deposits exposed on Upper Black Island in the Bay of Exploits (Figures 1 and 2); O'Brien *(this volume)* has assigned these sedimentary rocks to the Botwood Group (see Twenhofel and Shrock, 1937; Williams, 1962). The fauna is dominated by cyclopygid trilobites, which include:

Cyclopyge ?marginata Hawle and Corda, 1847
Psilacella sp. cf. *P. trinegata* Whittard, 1952
Symphysops subarmata elongata Kielan, 1960

The trinucleid trilobite *Tretaspis* sp. undet. and one unidentified strophomenid brachiopod were also collected.

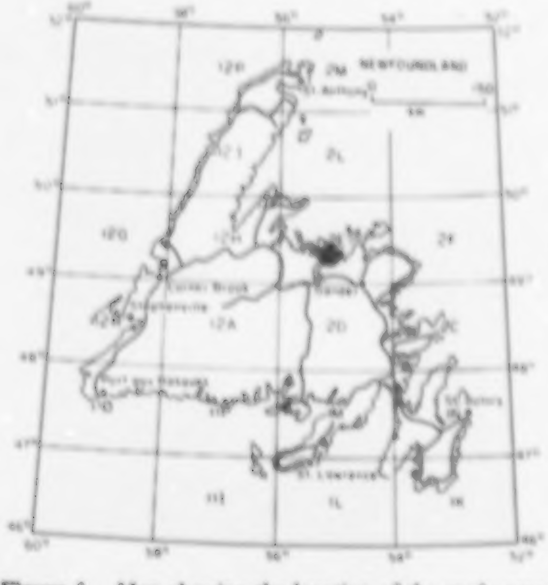


Figure 1. *Map showing the location of the study area.*

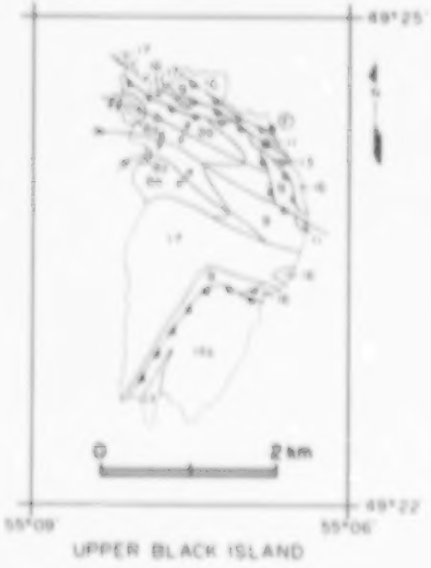
ENVIRONMENTAL SIGNIFICANCE OF CYCLOPYGID FAUNA

According to Fortey (1985, page 223) and Fortey and Owens (1987, page 105) cyclopygids probably swam at or about the limit of the photic zone (between 200 and 700 m water depth) near the edges of continental shelves and on upper slopes, or within deep marginal basins having free access to open ocean. The occurrence of Upper Black Island's cyclopygids in apparently slumped turbidites, indicative of a deep unstable slope, strongly supports Fortey's contention.

BIOSTRATIGRAPHIC SIGNIFICANCE OF CYCLOPYGID TRILOBITE FAUNA

The only previous record of cyclopygid trilobites in Newfoundland is that of Cocks (personal communication *in* Elliott *et al.*, 1989, page 2066, Table 1), who identified *Cyclopyge* sp. cf. *C. rediviva* (Barrande, 1846) along with the *trinucleid Dionide?* sp. from sandstone of the Sansom Formation exposed on the southwest shore of New World Island (Elliott *et al.*, 1989, Figure 2). *Cyclopyge rediviva* (Barrande, 1846) occurs in the Cernin Beds (Caradoc) of Trubin, Bohemia, Czechoslovakia.

Cyclopyge and *Psilacella* have long geological ranges, extending from the Arenig to the Ashgill (Fortey and Owens, 1987). *Symphysops* is an exceptionally widespread genus, occurring in Kazakhstan (U.S.S.R.), Quebec (Canada), Ireland, Poland, Bohemia (Czechoslovakia), Wales, Scotland, and China (Apollonov, 1974; Cooper and Kindle, 1936; Dean, 1974; Kielan, 1960; Marek, 1961; Price and Magor, 1984; Reed, 1914; Sheng, 1980). According to Kobayashi and Hamada (1971), *Symphysops* is restricted to Ashgill age rocks. However, in China the genus is reported from the *Sinoceras chinense* and *Nankinolithus nankinensis* zones of the Yenchingian Stage, equivalent to the Caradoc Series (Sheng, 1980, Table 4). Futhermore, Wright (*in* Whittington *et al.*, 1984, page 28) reports *Symphysops* from latest Caradoc (Onnian Stage) strata in the Upper Whitehouse Group of the Girvan district, Scotland.



from
MAP 90-124
Brien O'Brien
2E/6

LEGEND

SILURIAN OR DEVONIAN
SOUTH ARM GABBRO
17 *dykes, sills and sheets of gabbro, diorite and associated diabase and mafic pegmatite*

ORDOVICIAN AND SILURIAN
BOTWOOD GROUP
16 *unseparated units of limy shale, coticule-bearing argillite, calcareous sandstone, siliceous wacke and rare limestone; interbedded mafic flows, feldspathic wacke, mafic breccia and laminated argillite; olistostrome and conglomerate containing blocks of reefal limestone and mafic volcanic rocks*

ORDOVICIAN
POINT LEAMINGTON
14b *dark grey, carbonaceous shale and light grey, quartzofeldspathic wacke; olistostrome with black shale matrix.*
LAWRENCE HARBOUR SHALE
13 *unseparated units of black carbonaceous shale; black pyritiferous siltstone with black shale partings; grey chert with bioturbated black argillite laminae*
COBBS ARM LIMESTONE
11 *massive limestone; marble; interbedded limestone and calcareous wacke*

ORDOVICIAN OR EARLIER
LAWRENCE HEAD VOLCANICS
9 *mafic pillow lavas*
NEW BAY FORMATION
8a *thin-bedded grey shale; interbedded grey shale and sandy-to-pebbly wacke;* **8b** *feldspathic wacke and grey argillite; minor conglomeratic to pebbly wacke*

Figure 2. *Geology map of Upper Black Island showing cyclopygid trilobite locality.*

Cyclopyge marginata Hawle and Corda, 1847 and *Symphysops subarmata elongata* Kielan, 1960 are widespread Ashgill species. In Poland, they occur in the *Staurocephalus clavifrons* Zone (Kielan, 1960; Marek, 1961). As such, they are indicative of the Rawtheyan Stage (Ingham and Wright, 1970, page 238). The two species also occur together in the Ashgill of Kazakhstan (Apollonov, 1974). *Cyclopyge marginata* Hawle and Corda, 1847 also occurs in Bohemia (Marek, 1961), Quebec (Cooper and Kindle, 1936; Apollonov, 1974), and possibly Wales (Whittington, 1966); *Symphysops subarmata* elongata Kielan, 1960 has also been reported from Ireland (Dean, 1974).

Psilacella trirugata Whittard, 1952 was originally described from the 'cyclopygid beds' of the Upper Whitehouse Group of Girvan, Scotland. These strata were originally regarded as Ashgill (Whittard, 1952); however, they are now recognized as latest Caradoc, Onnian Stage (Ingham, 1978; Whittington *et al.*, 1984). Despite this, Apollonov (1974, page 27, Plate 10) also reports *Psilacella trirugata* Whittard, 1952 from the Ashgill (Chokparian) of Kazakhstan, which correlates with the Rawtheyan Stage. This indicates that the species may be long-ranging.

Ingham and Wright (1970, pages 237, 238) indicate that, in the Ashgill, the trinucleid genus *Tretaspis* occurs in Pusgillian, Cautleyan and Rawtheyan strata. According to Fortey and Chatterton (1988; Text figure 27), only one trinucleid genus *(Raphiophorus)* survived past the Ashgill. This means that the Upper Black Island fossil locality is no younger than Ashgill.

To summarize, based on the presence of *Cyclopyge ?marginata* Hawle and Corda, 1847, *Symphysops subarmata elongata* Kielan, 1960, and *Tretaspis* sp. undet., the Upper Black Island fossil locality is probably Ashgill (Rawtheyan) in age. The occurrence of *Psilacella* sp. cf. *P. trirugata* Whittard, 1952 certainly indicates an age no older than latest Caradoc (Onnian).

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REFERENCES

Apollonov, M.K.
1974: Ashgill'skiye Trilobiti Kazakhstana. Akadyemiya Nauk Kazakhskoi CCP, Ordyena Trudovogo Krasnogo Znamyenyi, Institut Geologicheskyikh Nauk im. K. M. Satpayeva, Izdatyel'stvo Nauka Kazakhskoi CCP (ALMA-ATA), 136 pages.

Cooper, G.A. and Kindle, C.H.
1936: New brachiopods and trilobites from the Upper Ordovician of Percé, Quebec. Journal of Paleontology, Volume 10, pages 348-372.

Dean, W.T.
1974: The trilobites of the Chair of Kildare Limestone (Upper Ordovician) in eastern Ireland. Part 2. Palaeontographical Society Monograph, pages 61-98; Plates 37-46.

Elliott, C.G., Barnes, C. and Williams, P.F.
1989: Southwest New World Island stratigraphy: new fossil data, new implications for the history of the Central Mobile Belt, Newfoundland. Canadian Journal of Earth Sciences, Volume 26, pages 2062-2074.

Fortey, R.A.
1985: Pelagic trilobites as an example of deducing the life habits of extinct arthropods. Transactions of the Royal Society of Edinburgh, Volume 76, pages 219-230.

Fortey, R.A. and Chatterton, B.D.E.
1988: Classification of the trilobite suborder Asaphina. Palaeontology, Volume 31, pages 165-222.

Fortey, R.A. and Owens, R.M.
1987: The Arenig Series in south Wales. Bulletin of the British Museum of Natural History (Geology), Volume 41, pages 69-307.

Ingham, J.K.
1978: Geology of a continental margin 2: middle and late Ordovician transgression. *In* Crustal Evolution in Northwestern Britain and Adjacent Regions. *Edited by* D.R. Bowes and B.E. Leake. Geological Journal, Special Issue 10, pages 153-176.

Ingham, J.K. and Wright, A.D.
1970: A revised classification of the Ashgill Series. Lethaia, Volume 3, pages 233-242.

Kielan, Z.
1960: Upper Ordovician trilobites from Poland and some related forms from Bohemia and Scandinavia. Palaeontologica Polonica, Number 11, 198 pages.

Kobayashi, T. and Hamada, T.
1971: Contributions to the geology and palaeontology of southeast Asia. No. 78. A cyclopygid-bearing Ordovician faunule discovered in Malaya with a note on the Cyclopygidae. Geology and Palaeontology of Southeast Asia, Volume 8, pages 1-18.

Marek, L.
1961: The trilobite family Cyclopygidae Raymond in the Ordovician of Czechoslovakia. Rozpravy Ustredniho ustavu geologického, Volume 28, pages 1-84.

O'Brien, B.H.
This volume: Geological development of the Exploits and Notre Dame subzones in the New Bay area (parts of 2E/6 and 2E/11), Notre Dame Bay, Newfoundland.

Price, D. and Magor, P.M.
1984: The ecological significance of variation in the generic composition of Rawtheyan (Late Ordovician) trilobite faunas from North Wales, U.K. Geological Journal, Volume 19, pages 187-200.

Reed, F.R.C.
1914: The Lower Palaeozoic trilobites of the Girvan district, Ayrshire. Supplement. Palaeontographical Society Monograph, 56 pages.

Sheng, S.-F.
1980: The Ordovician System in China: correlation chart and explanatory notes. International Union of Geological Sciences, Publication Number 1, 7 pages.

Twenhofel, W.H. and Shrock, R.R.
1937: Silurian strata of Notre Dame Bay and Exploits Valley, Newfoundland. Geological Society of America Bulletin, Volume 48, pages 1743-1772.

Whittard, W.F.
1952: Cyclopygid trilobites from Girvan and a note on *Bohemilla*. Bulletin of the British Museum of Natural History (Geology), Volume 1, pages 305-324.

Whittington, H.B.
1966: The Ordovician trilobites of the Bala area, Merioneth. Part 3. Palaeontographical Society Monograph, pages 63-92; Plates 19-28.

Whittington, H.B., Dean, W.T., Fortey, R.A., Rickards, R.B., Rushton, A.W.A. and Wright, A.D.
1984: Definition of the Tremadoc Series and the series of the Ordovician System in Britain. Geological Magazine, Volume 121, pages 17-33.

Williams, H.
1962: Botwood (West Half) map-area, Newfoundland (2E W1/2). Geological Survey of Canada, Paper 62-9, 16 pages.

Current Research (1990) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 90-1, pages 83-84

MIDDLE CAMBRIAN TRILOBITES FROM TOPSAIL HEAD, AVALON PENINSULA

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ABSTRACT

Most regional geology maps incorporating Topsail Head have not separated the Cambrian strata from the Harbour Main Group. Along the Topsail Fault, north of Topsail Beach, green, grey and black shales and siltstones of the Cambrian Adeyton and Harcourt groups are juxtaposed against mafic volcanic rocks of the Precambrian Harbour Main Group. Middle Cambrian trilobites and inarticulate brachiopods were obtained from two horizons within the Chamberlain's Brook Formation (Adeyton Group). One horizon, within the Manuels River Formation (Harcourt Group), yielded unidentifiable trilobite and inarticulate brachiopod remains.

INTRODUCTION

Along the Topsail Fault, north of Topsail Beach, green, grey and black shales and siltstones of the Cambrian Adeyton and Harcourt groups are juxtaposed against mafic volcanic rocks of the Precambrian Harbour Main Group (Figures 1 and 2). Most regional geology maps have combined the Cambrian strata with the Harbour Main Group and placed the fault along the beach (i.e., Rose, 1952). In reality, the trace of the fault is marked by a break in slope, inland, and the Cambrian strata are well exposed along the beach parallel to the fault (Dawson, 1963; Hayes and O'Driscoll, 1989).

BIOSTRATIGRAPHY

Middle Cambrian trilobites and inarticulate brachiopods were obtained from two horizons within the Chamberlain's Brook Formation (Adeyton Group). Near the Topsail Beach parking area (Figure 2, Locality 'A'), blue-grey and blue-green shale and siltstone yielded *Eccaparadoxides lamellatus* (Hartt *in* Dawson, 1868). Further north, a distinctive massive, brown weathering, dark blue-grey trilobite coquina bed was found (Figure 2, Locality 'B'); it is probably analogous to the 'rottenstone' marker bed of the Kelligrews' Quarries (Boyce, 1988, page 49). Although the fossils are structurally deformed, the following have been identified:

Brachiopoda-Inarticulata
    Gen. et sp. undet.

Trilobita
    Bailiaspis elegans (Hartt *in* Dawson, 1868)
    Conocephalus terranovicus Resser, 1937
    Eccaparadoxides lamellatus (Hartt *in* Dawson, 1868)

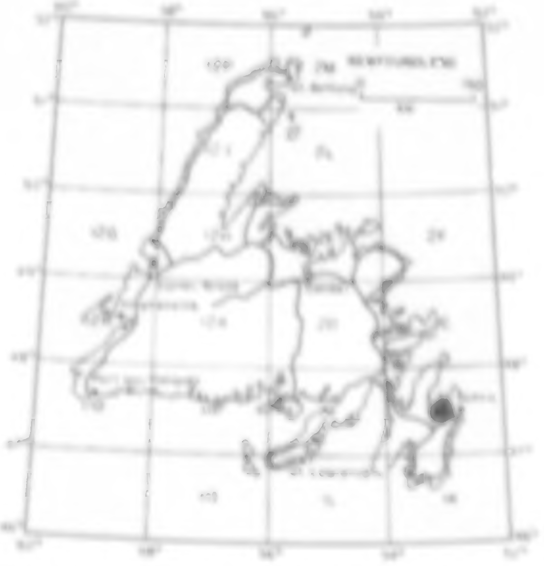
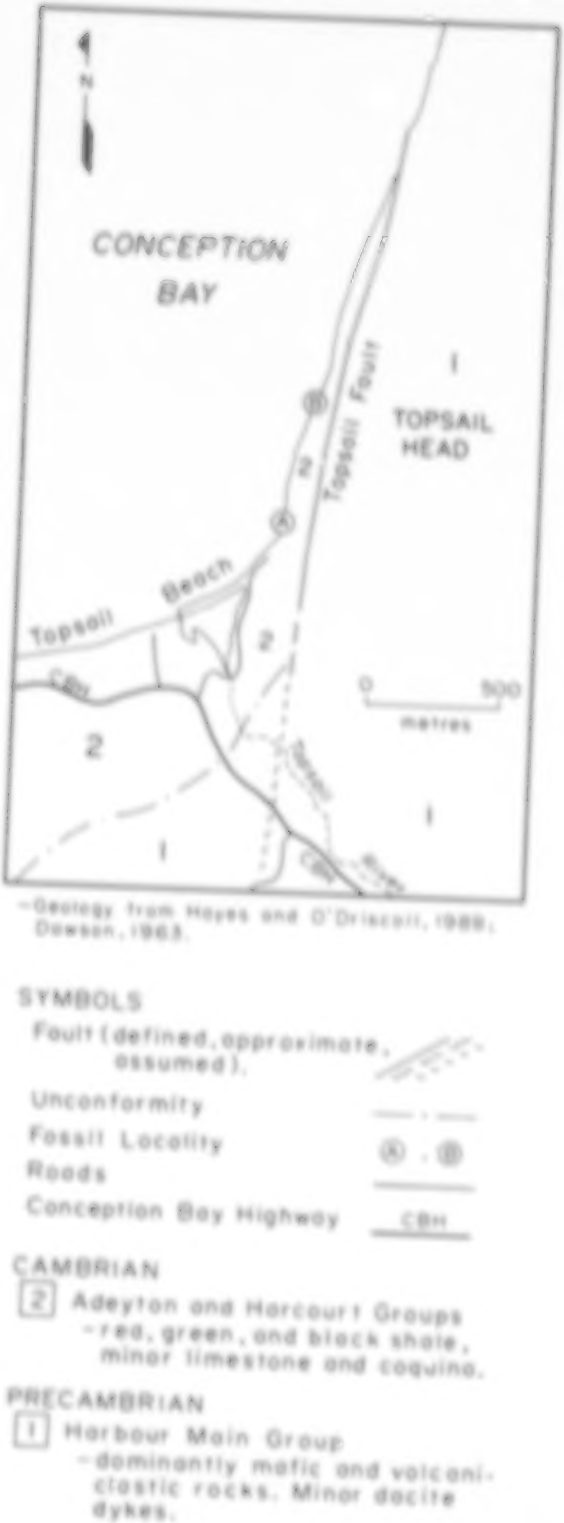


Figure 1. *Location of Topsail Head area.*

The fossils from both localities are indicative of an early Middle Cambrian *Eccaparadoxides bennetti* Zone age (see Boyce, 1988, Figure 5).

Dark-grey to black shale and slate of the Manuels River Formation (Harcourt Group) yielded unidentifiable trilobite and inarticulate brachiopod remains.

Rose (1952, page 32) reported that the Late Cambrian Elliott Cove Formation is exposed along Topsail Head, but listed no fossils.


N
CONCEPTION BAY
Topsail Fault
1
TOPSAIL HEAD
B
2
A
Topsail Beach
2
CBH
0
500
metres
2
1
1
CBH
SYMBOLS
Fault (defined, approximate, assumed).
Unconformity
Fossil Locality
Roads
Conception Bay Highway
CBH
CAMBRIAN
2
Adeyton and Harcourt Groups
-red, green, and black shale, minor limestone and coquina.
PRECAMBRIAN
1
Harbour Main Group
-dominantly mafic and volcaniclastic rocks. Minor dacite dykes.

-Geology from Hayes and O'Driscoll, 1989; Dawson, 1963.

Figure 2. *Geology map of Topsail Head area showing location of fossil collections.*

REFERENCES

Boyce, W.D.
1988: Cambrian trilobite faunas on the Avalon Peninsula, Newfoundland. Trip A8. Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists, Fieldtrip Guidebook, 77 pages.

Dawson, J.
1963: Regional geology of the Topsail–Foxtrap area. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, 124 pages. [1N(72)]

Hayes, J.P. and O'Driscoll, C.F.
1989: The geology of the eastern Avalon high-alumina belt (parts of 1N/10 and 1N/7). Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File Map 89-149A and B.

Rose, E.R.
1952: Torbay map-area, Newfoundland. Geological Survey of Canada, Memoir 265, 64 pages.

NOTE: Geological Survey Branch file numbers are included in square brackets.

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Geological Survey Branch, Report 91-1, pages 85-89

GEOLOGY AND TECTONIC SIGNIFICANCE OF THE RAMEA ISLANDS, NEWFOUNDLAND

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ABSTRACT

Tectonostratigraphic correlations place the Ramea Islands within the Paleozoic Gander Zone of the Appalachian Orogen, whereas correlations based on geophysical studies, and corroborated by the presence of Precambrian rocks at Grey River and Cinq Cerf, place the islands within a Precambrian terrane, i.e., the Avalon Zone or the Bras d'Or Terrane.

The Ramea Islands are underlain entirely by plutonic rocks of unknown age. The earliest major unit is a 1-km-wide belt of mylonitized, feldspar porphyritic, biotite granite that has been intruded by biotite granites, gabbro and diabase. Mylonitization occurs within a dextral shear system. The post-mylonitization granite along the northwest-facing coast is extensively brecciated.

The mylonitic granite is similar to one 60 km to the east, on the south coast of Newfoundland, which has been correlated with the Gaultois Granite, a characteristic rock of the Gander Zone. The latest posttectonic granite and the mafic intrusions on the Ramea Islands are similar to Devonian or younger correlatives along the south coast of Newfoundland. The Ramea Islands lie southwest of the Precambrian Grey River enclave. Their possible correlation with the Gander Zone implies a tectonic contact with the enclave. Easterly trending aeromagnetic anomalies between the Ramea Islands and the south coast may also indicate that they form part of a separate block.

INTRODUCTION

The Ramea Islands are situated 6 km off the south coast of Newfoundland and are about 20 km southeast of Burgeo (Figure 1). The islands are underlain by gabbroic to granitic rocks (Figure 2) that have been correlated with the Siluro-Devonian Burgeo Intrusive Suite on the adjacent south coast of Newfoundland (Dickson *et al.*, 1985; O'Brien *et al.*, 1986).

REGIONAL TECTONIC SETTING

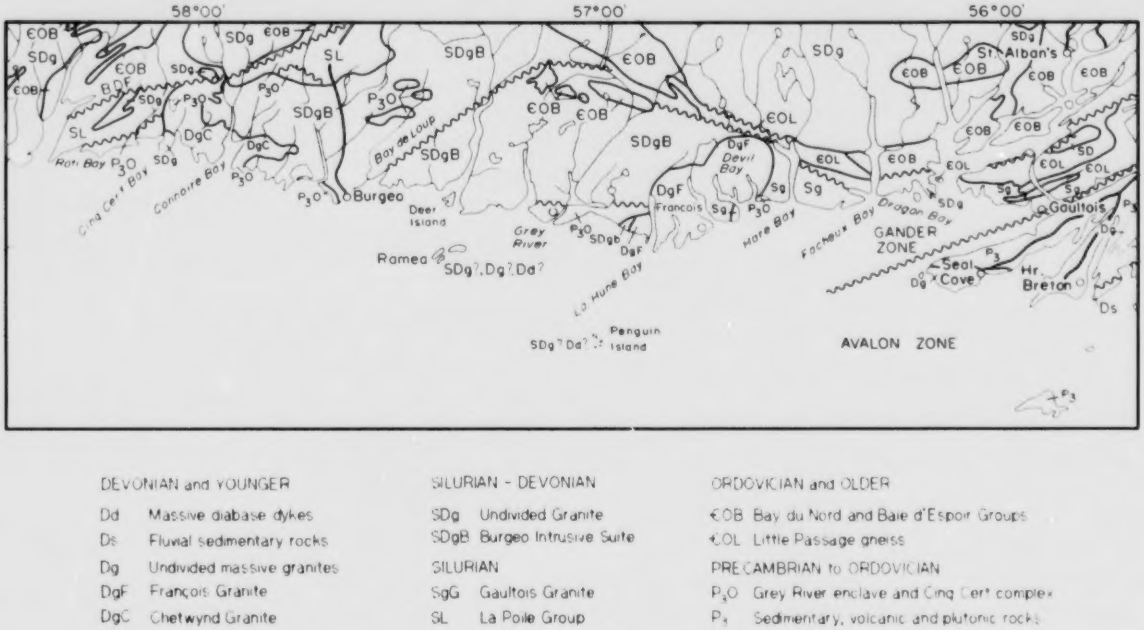
The granitoid rocks of the Ramea Islands and the Siluro-Devonian Burgeo Intrusive Suite are shown by O'Brien *et al.* (1986), Williams *et al.* (1989) and Dickson *et al.* (1989) to lie within the Gander Zone of the Appalachian Orogen on the basis of lithological similarities with typical Gander Zone intrusive rocks in northeastern Newfoundland (Figure 3). Similarly, based upon offshore, deep-seismic data Marillier *et al.* (1989) show that the Burgeo Intrusive Suite and the Ramea Islands lie well north of the Avalon Zone boundary and within the Gander Zone (Figure 3).

Metamorphic rocks in the Grey River area (Grey River enclave of Blackwood, 1985; Figure 1), were shown by Williams (1971) and Howarth and Lefort (1979) to be possible correlatives of the Avalon Zone. Dunning and O'Brien (1989) dated units of the enclave and others at Cinq Cerf (75 km west of Ramea) and obtained Late Precambrian to Early Ordovician dates from gneissic, plutonic and volcanic units (see also Stewart and Dunning, 1990); these data indicate a possible affiliation with the Avalon Zone. An east-trending shear zone separates the Grey River enclave from the adjacent Siluro-Devonian Burgeo Intrusive Suite. Precambrian strata at Cinq Cerf are locally unconformably overlain by, but are mainly in fault contact with, Silurian strata (O'Brien and O'Brien, 1990).

TRANS-GULF CORRELATIONS

Southeastern Cape Breton Island is considered by Barr and Raeside (1986) to be composed of two terranes known as the Bras d'Or and Mira terranes, which formed the continuation of the Newfoundland Avalon Zone (Figure 3). More recently, Barr and Raeside (1989) restricted this correlation to the Mira Terrane and proposed that the Late Precambrian history of the Bras d'Or Terrane is distinct from that of the Mira Terrane.

The Bras d'Or Terrane (Figure 3) of Cape Breton Island consists of Late Precambrian to Early Ordovician gneisses, metasedimentary and metavolcanic, and abundant plutonic rocks. This terrane is correlated with the Cinq Cerf and Grey River blocks of southern Newfoundland (Barr and Raeside, 1989). The Ramea Islands and the adjacent Burgeo Intrusive Suite are shown by Loncarevic *et al.* (1989), Barr and Raeside (1989), Dunning *et al.* (1990) to lie within the Bras d'Or Terrane.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ЄOB
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SgG
Sg
Ds
Dg
Rot. Bay
Cinq Cerf Bay
Connoire Bay
Bay de Loup
Burgeo
Deer Island
Grey River
Ramea
SDg?, Dg?, Dd?
La Hune Bay
Penguin Island
SDg? Dd?
Francois
Devil Bay
Hare Bay
Facheux Bay
Dragon Bay
GANDER ZONE
AVALON ZONE
Seal Cove
Hr. Breton
Gaultois
St. Alban's
DEVONIAN and YOUNGER
Dd Massive diabase dykes
Ds Fluvial sedimentary rocks
Dg Undivided massive granites
DgF François Granite
DgC Chetwynd Granite
SILURIAN - DEVONIAN
SDg Undivided Granite
SDgB Burgeo Intrusive Suite
SILURIAN
SgG Gaultois Granite
SL La Poile Group
ORDOVICIAN and OLDER
ЄOB Bay du Nord and Baie d'Espoir Groups
ЄOL Little Passage gneiss
PRECAMBRIAN to ORDOVICIAN
P3O Grey River enclave and Cinq Cerf complex
P3 Sedimentary, volcanic and plutonic rocks

Figure 1. *Regional setting of the Ramea Islands (based on Colman-Sadd et al., 1990). BDF = Bay d'Est Fault.*

The Bras d'Or and Mira terranes are correlated with the Avalon Zone by Marillier *et al.* (1989). The submarine position of the Gander–Avalon Zone contact between Newfoundland and Cape Breton Island is only inferred by Marillier *et al.* (1989; Figure 3). Keppie *et al.* (1990) and Keppie (1990) also prefer to include the Bras d'Or Terrane in their 'Avalon Composite Terrane' arguing that significant correlations of Late Proterozoic to Carboniferous units can be made across the proposed Bras d'Or–Mira terrane boundary of Barr and Raeside (1989). The Ramea units, which in the various Precambrian terrane models apparently lie outside the Gander Zone (Terrane), should show some affinity to the plutonic rocks of either the Avalon (and/or Mira) terrane or the Bras d'Or Terrane.

ROCK TYPES OF THE RAMEA ISLANDS

The Ramea Islands are underlain by a variety of mylonitic, brecciated and massive intrusive rocks (Figure 2). High-grade metamorphic or gneissic metasedimentary units are absent, although biotite-rich, possibly metasedimentary xenoliths occur locally. Foliated and metamorphosed, hornblende–biotite granite (subunit 2b) occurs in the eastern part of the Ramea Islands but this unit is probably related to the Unit 2 mylonitic granite.

The oldest unit is represented by several 1000 m^2 variably deformed or massive metagabbroic inclusions (Plate 1) within granitic Units 2, 3 and 5 (Figure 2). Some inclusions are polydeformed and contain porphyroblasts of actinolite related to contact metamorphism by the enclosing granites.

A northeast-trending, 1-km-wide belt of intensely deformed granite (Unit 2) occurs on both sides of the northeast-trending channel, south of Northwest Island, and continues to the east along the southern edge of Main Island. The granite consists of fractured, 1- to 2-cm-long, perthitic K-feldspar and plagioclase augen in a green-black, fine-grained, granoblastic matrix of quartz, amphibole, titanite and opaques (Plate 2; see also Plates 8 and 9). The most deformed parts of the granite contain black, very fine-grained, parallel mylonite zones (subunit 2a). Near the eastern end of Great Island, the granite of subunit 2b consists K-feldspar porphyroclasts, which have recrystallized to form euhedral subgrains, in a matrix of polygonized quartz, aligned biotite and randomly oriented fresh actinolitic hornblende porphyroblasts.

Massive, medium-grained, equigranular and K-feldspar porphyritic, biotite ± hornblende granite (Unit 3) extends from Ramea Colombier island northeastward to the eastern end of Great Island (Plate 3; Figure 2). The contact of Unit 3 with Unit 2 is intrusive; massive granite dykes of Unit 3 cut the mylonites (Plate 4) and xenoliths of mylonitic Unit 2 occur within Unit 3. The northwestern portion of Unit 3 is highly brecciated and cut by numerous anastomosing, brittle shears (Plate 5). A small intrusion of massive, biotite–hornblende granodiorite (Unit 4) outcrops at the eastern end of Great Island and contains xenoliths of Unit 3.

Massive, pink, fine- to medium-grained, leucocratic biotite granite (Unit 5) has intruded the mylonitic granite (Unit 2), east of Ramea Harbour (Plate 6). A similar granite outcrops at Northwest Head (S.J. O'Brien, personal communication, 1990) and this granite may be the source of the nearby massive granitic dykes that cut the mylonitic granite. Various massive to weakly cleaved felsic dykes (Unit 6) have intruded the earlier granites.

Medium-grained, massive, biotite–hornblende gabbro (Unit 7) outcrops at the southern edge of Ramea Harbour. The gabbro has intruded the mylonitic granite and is probably intrusive into the massive granite (Unit 5). Diabase dykes (Unit 8) occur throughout the area (Plate 7). At the southern entrance to Ramea Harbour, diabase forms a 500-m-wide plug.

STRUCTURAL FEATURES OF THE RAMEA ISLANDS

The dominant structure in the Ramea Islands area is a major northeast-trending, steeply dipping, ductile shear zone restricted to Unit 2. Deformation is most intense along the main channel having 1- to 5-m-wide, parallel, 060°-trending, steeply dipping zones of black, flinty mylonite within porphyroclastic granite, which has a mylonitic matrix. Toward the unit margins, the granite is dominated by porphyroclastic granite having narrow (1 cm), anastomosing bands of black, fine-grained mylonite. Locally, the porphyroclastic granite is folded into open folds (Plate 8).

Asymmetric feldspar porphyroclasts indicate that shearing was mainly dextral. Mafic psammitic xenoliths are elongate having subhorizontal long axis parallel to the foliation (Plate 9). Mineral lineations are rare and plunge gently to the southwest; definitive C-S fabrics were not found.

The shear zone clearly predates intrusion of Units 3 and 5. Xenoliths of mylonitic granite occur within Unit 3 and granite veins crosscut the mylonitic fabric. The veins locally contain a weak fabric that is parallel to the mylonitic fabric and axial planar to open folds of the granite veins. The mylonitic fabric is locally overprinted by an east-trending fracture cleavage.

A 500-m- to 1-km-wide belt of brittle fracturing and shearing occurs along the northwest side of Northwest Island and Great Island (subunit 3a). The fracturing intensity and shearing increases to the northwest and north on Northwest Island and Great Island, respectively. This extensive zone of brecciation indicates that a major, late fault lies to the northwest of the islands. Several massive, post-brecciation diabase dykes have intruded along later, mainly northwest-trending faults.

GEOPHYSICAL EXPRESSION

In the gravity and magnetic compilations of Loncarevic *et al.* (1989), the Ramea Islands lie in an area of high gravity and magnetic anomalies that continue eastward to the western margin of the Avalon Zone. These anomalies define the Bras d'Or Terrane. The northern limit of these anomalies almost coincides with the northern contact of the Burgeo Intrusive Suite, which is also the site of several major shear zones (see O'Brien and Dickson, 1986). The gravity data do not show this boundary, which is presumed by Loncarevic *et al.* (1989) to be masked by the granitic rocks. Howarth and Lefort (1979) tentatively proposed that the northern limit of the Avalon Zone along the south coast of Newfoundland lay within the area of the Burgeo Intrusive Suite. This was based on the extent of magnetic zones similar to those of the Avalon Zone in eastern Newfoundland, the presence of Avalon Zone equivalent rocks at Grey River (from Williams, 1971), and the location of northwest-trending magnetic lows that coincided with presumed tear faults. The Burgeo Intrusive Suite was assumed to have intruded the Avalon–Gander Zone boundary.

The aeromagnetic total-field map for the Ramea map area (GSC 1986; Figure 4; see also Loncarevic *et al.*, 1989) shows that the Ramea Islands lie at the southeastern margin of an eastward-trending series of magnetic lows. The northern margin of these lows could represent the edge of the Burgeo Intrusive Suite and the Grey River enclave. The aeromagnetic low, which extends northwestward from the Ramea Islands, may indicate the extent of a separate Ramea Islands block.

SUMMARY OF SOUTH COAST GEOLOGY

A brief summary of the five main geological elements along the south coast is presented to assess possible correlations with Ramea.

The Grey River enclave comprises a sequence of late Precambrian migmatitic gneisses, pretectonic mafic intrusions and Cambrian metavolcanic and metasedimentary rocks (Unit P_3O; Figure 1) and minor massive leucocratic granite (Blackwood, 1985; Dunning and O'Brien, 1989). The northern contact of the enclave with the Burgeo Intrusive Suite is an east-trending zone of intense mylonitization and later brecciation. The southeastern portion of the enclave is intruded by a massive metagabbro, which is in turn intruded by the François Granite. East of Devil Bay (Figure 1), a thin sliver of strongly foliated volcanic rocks are correlated with the volcanic rocks of the Grey River enclave (see O'Brien *et al.*, 1986).

The Burgeo Intrusive Suite is a composite 3000-km^2 batholith (O'Brien *et al.*, 1986), from which two foliated units have been dated at 428 and 415 ± 2 Ma by Dunning *et al.* (1988). Along the south coast, the batholith is dominated by coarse-grained, massive to brecciated, feldspar porphyritic, biotite granites and granodiorites. Massive, K-feldspar megacrystic granite, from 3 to 5 km north of Grey River, is dated at 412 ± 5 Ma (Rb–Sr whole-rock isochron; initial $^{87}Sr/^{86}Sr$ ratio = 0.7086) by Higgins *et al.* (1990). Metagabbro is relatively abundant on a few islands southwest of Burgeo (O'Brien and Tomlin, 1985) where it is intruded by the granite.

The northern limit of the suite is approximately the northwest-trending Dragon Bay Fault and the northeast-trending Bay d'Est Fault, which partly coincide with the intrusive contact of the suite with the Middle Ordovician strata (Figure 1). C-S fabrics in granites from the Dragon Bay Fault indicate dextral movement (see also Piasecki *et al.*, 1990). To the west of the Grey River enclave, the granites are highly faulted, commonly brecciated, locally mylonitized and

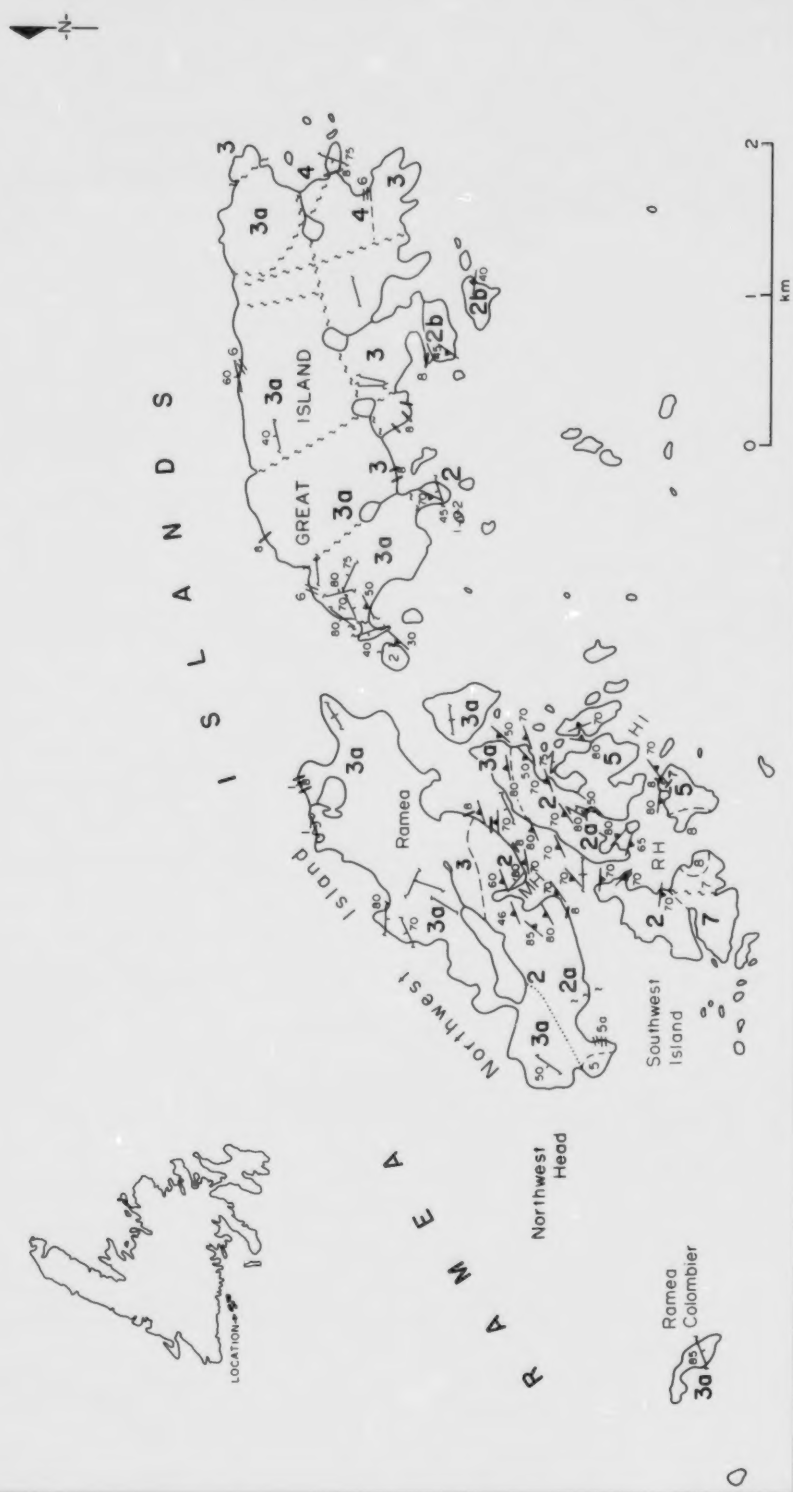

N
RAMEA ISLANDS
GREAT ISLAND
Ramea Island
Northwest Island
Southwest Island
Northwest Head
Ramea Colombier
LOCATION
HI
MH
RH
0
1
2
km

Figure 2. *Geology of the Ramea Islands. HI—Harbour Island, MH—Muddy Harbour, RH—Ramea Harbour.*

LEGEND for Figure 2

?DEVONIAN OR YOUNGER

8	*Massive, medium-grained diabase plug and dykes*
7	*Massive, medium-grained, biotite–hornblende quartz diorite and gabbro*
6	*Felsic dykes of uncertain affiliation*
5	*Massive to weakly cleaved, pink, equigranular, leucocratic, biotite granite;* **5a**, *fine-grained granite dykes*

?SILURIAN - DEVONIAN OR OLDER

4	*Grey, massive to sheared, medium-grained, equigranular biotite–hornblende granodiorite*
3	*Pink, massive, medium, coarse-grained, K-feldspar-porphyritic, biotite granite;* **3a**, *pink, fractured and sheared, medium to medium-coarse grained, equigranular to K-feldspar-porphyritic, biotite granite*
2	*Black and pink, medium- to coarse-grained, K-feldspar porphyroclastic, strongly foliated to mylonitic biotite granite;* **2a**, *black, fine to very fine grained, feldspar porphyroclastic, mylonitic granite;* **2b**, *black and pink, foliated, medium-grained, metamorphosed, K-feldspar-porphyroclastic, biotite granite*
1	*Medium- to coarse-grained, massive to foliated metagabbro and diabase xenoliths*

Symbols

Fault (approximate)

Mylonitic foliation (inclined, vertical)

Brittle shear fabric (inclined, vertical)

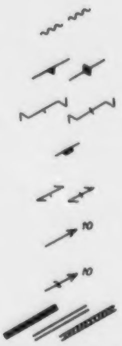
Mineral layering (inclined)

Cleavage (inclined, vertical)

Mineral lineation (with inclination)

Crenulation lineation (with inclination)

Dykes (mafic, felsic, granitic)



contain a weak, east-trending cleavage. These features are restricted to a 3-km-wide zone that parallels the coast and is terminated by the northeast-trending Bay de Loup Fault.

The Gaultois Granite is an elongate body of strongly foliated to mylonitic, coarse-grained, feldspar-porphyritic, biotite ± hornblende granite and granodiorite located 50 km east-northeast of the Ramea Islands. The granite at its type area has been dated at 421 Ma (U–Pb zircon) and 417 Ma (U–Pb titanite; Dunning *et al.*, 1990). The northern margin of the granite is extensively mylonitized along the Dragon Bay Fault. Some of the foliated, biotite-rich granites of the Burgeo Intrusive Suite are similar to the Gaultois Granite and these may be correlatives.

A thin sliver of strongly sheared and foliated volcanic rocks, correlated with the Grey River enclave (see Dickson *et al.*, 1984), separates the main mass of the Gaultois Granite from a similar granite located southwest of Devil Bay. This granite is locally transformed into a black, fine-grained mylonite having a generally northeast-trending, steep-dipping foliation. In comparison, the Gaultois Granite northeast of Devil Bay is generally less deformed, has a moderately north-dipping foliation, is more mafic, coarser grained and more coarsely porphyritic. However, the intensity of deformation within the main mass of the Gaultois Granite and the dip of the foliation increases toward the sliver of volcanic rocks. The two areas of granite are probably equivalent.

A series of highly evolved, posttectonic, Early to Late Devonian granites have intruded across the faulted contacts between the Precambrian sequences and adjacent blocks at Grey River and Cinq Cerf (see Dunning *et al.*, 1990). Other shear zones, such as the Dragon Bay Fault, Bay d'Est Fault and the Hermitage Bay–Dover Fault, are also cut by these granites. The granites are not centred on the shear zones but form a linear belt of intrusions that intrude both terranes along the entire south coast of Newfoundland (Dickson *et al.*, 1988).

Posttectonic diabase dykes are concentrated along the south coast and are particulary abundant in the Grey River

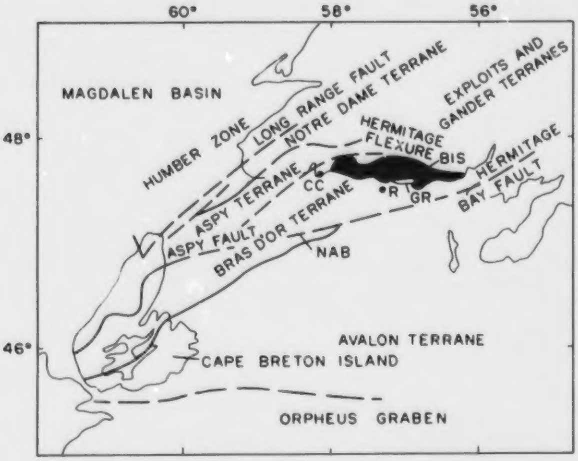

60°
58°
56°
48°
46°
MAGDALEN BASIN
HUMBER ZONE
LONG RANGE FAULT
NOTRE DAME TERRANE
EXPLOITS AND GANDER TERRANES
HERMITAGE FLEXURE
BIS
HERMITAGE BAY FAULT
ASPY TERRANE
CC
R
GR
ASPY FAULT
BRAS D'OR TERRANE
NAB
AVALON TERRANE
CAPE BRETON ISLAND
ORPHEUS GRABEN

Figure 3. *Tectonostratigraphic correlations between Newfoundland and Cape Breton Island (based on Barr and Raeside, 1989). CC–Cinq Cerf area; R–Ramea Islands; GR–Grey River enclave; BIS–Burgeo Intrusive Suite and other granitic units; NAB–inferred northern Avalon Zone boundary of Marillier et al. (1989); note that according to Marillier et al. (1989), the Bras d'Or Terrane in Cape Breton Island is part of the Avalon Zone, whereas in Newfoundland, it forms part of the Gander Zone.*

Plate 1. *Metagabbro inclusion (Unit 1) net-veined by granite derived from Unit 3; north shore of Great Island.*

enclave and in the François Granite, west of the entrance to La Hune Bay. The Penguin Islands contain an abundance of diabase dykes that cut the massive Penguin Islands Granite (Figure 1; see also O'Brien *et al.*, 1986). Very few dykes occur inland within the Paleozoic units. Several generations of diabase dykes cut the Grey River enclave and include pre-, syn- and posttectonic dykes (see Bahyrycz, 1957; Higgins and Smyth, 1980; and Blackwood, 1985). At Penguin Islands, the 2- to 5-m-thick, early dykes are extensively back-veined by the host granite and crosscut by 20-cm-wide later dykes.

Plate 2. *Intensely foliated, porphyroclastic biotite granite (Unit 2); small island north of Ramea Harbour.*

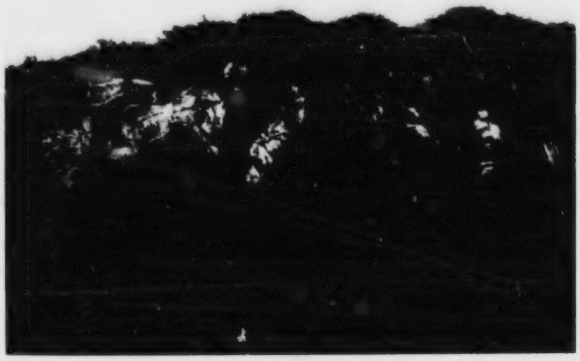


Plate 3. *Mylonitic granite (Unit 2) cut by massive, light-coloured massive granite dykes (Unit 3); north side of Muddy Harbour.*

Plate 4. *Massive biotite granite (Unit 3) containing flow-aligned K-feldspar phenocrysts; along coast south of Gull Hill, Great Island.*

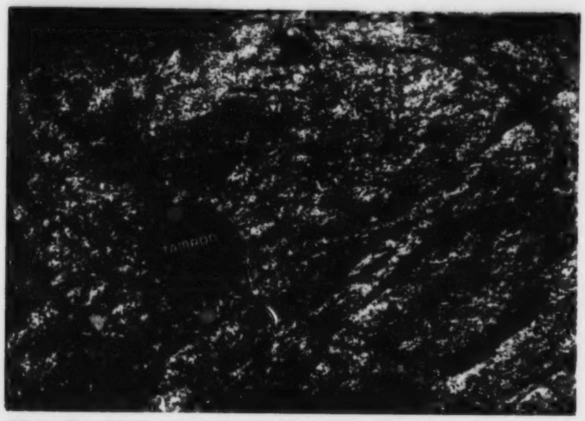


Plate 5. *Medium-grained, brecciated biotite granite (Unit 3e); western end of Great Island.*

Plate 6. *Mylonitic granite (Unit 2) containing steeply-dipping foliation cut by massive fine-grained granite dyke (Unit 5); northeastern side of Harbour Island.*

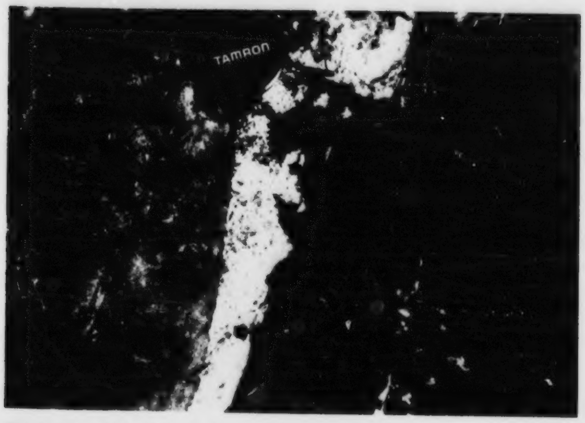


Plate 7. *Massive diabase dykes (Unit 8) cuts massive granite (Unit 3); along coast south of Gull Hill, Great Island.*

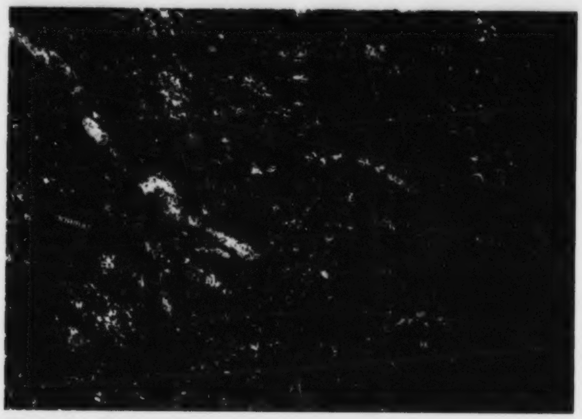


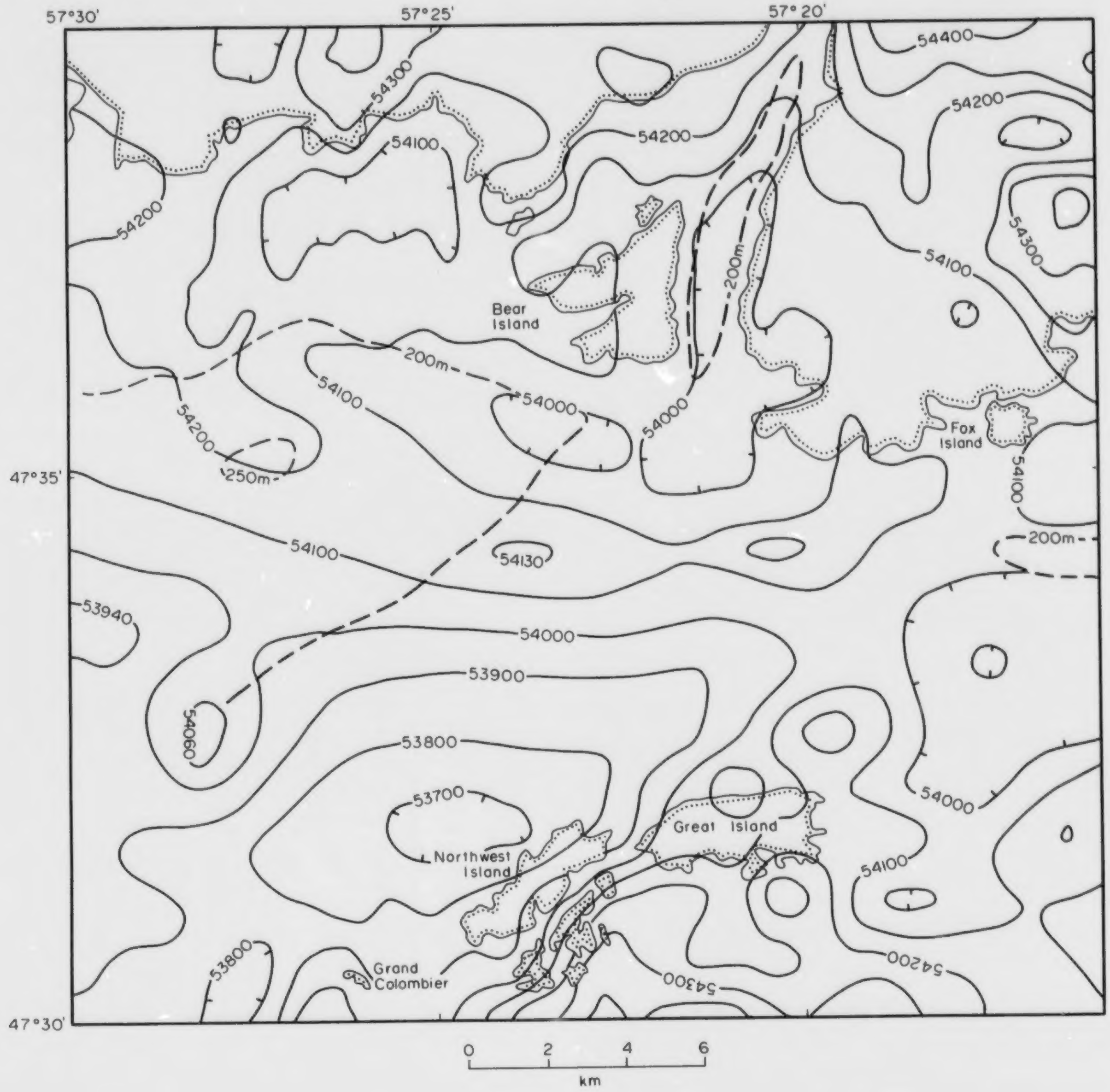
Plate 8. *Foliated mylonitic granite folded into asymmetric open fold; north side of Ramea Harbour.*

Plate 9. *Mafic psammitic xenolith elongated parallel to the mylonitic foliation in porphyroclastic biotite granite (Unit 2); road-cut north of Muddy Harbour.*

POSSIBLE LITHOLOGICAL AND STRUCTURAL CORRELATIONS

Metagabbroic and diabasic inclusions occur in the Ramea Islands and throughout the Burgeo Intrusive Suite (O'Brien *et al.*, 1986). The mylonitic porphyritic granite at Ramea is virtually identical to the presumed Gaultois Granite southwest of Devil Bay. The posttectonic leucocratic granites occur throughout the south coast region and have similar structural settings. The diabase dykes found throughout the coastal zone are probably correlatives.

The brecciated granite (Unit 3), minor granodioritic and gabbroic units (Units 4 and 7) at Ramea have no obvious correlatives. It must be emphasized that the pre- and syntectonic plutonic rocks of the Grey River enclave and Cinq Cerf area have no correlatives in Ramea. Similarly, the pre-François Granite and pre-massive diabase components of the enclave are not found on the Ramea Islands.


57°30'
57°25'
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54400
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Bear Island
200m
54100
54000
54200
250m
54000
Fox Island
54100
200m
54100
54130
53940
54000
53900
54060
53800
53700
Northwest Island
Great Island
54000
54100
54200
54300
53800
Grand Colombier
0
2
4
6
km

Figure 4. *Aeromagnetic total field map of the Ramea area (simplified from GSC Map 9649G, 1986). Isomagnetic lines in gammas—solid lines; submarine contours in metres—dashed lines.*

Tectonic similarities include the major shear zone within Unit 2 at Ramea, which may be associated with the mylonitization in the presumed Gaultois Granite, southwest of Devil Bay. The brecciation of Unit 3 in Ramea may be related to that along the southern edge of the Burgeo Intrusive Suite. The dextral movement of faults along the south coast is comparable with the probable dextral movement within the mylonites at Ramea. The Ramea shear zone may form part of the major shear system described by Piasecki *et al.* (1990) as having developed in this region during the Ordovician and Silurian.

DISCUSSION

The correlation of the Ramea Islands plutonic rocks with the Silurian Burgeo Intrusive Suite by Dickson *et al.* (1985) implied that the island's plutonic rocks lie within the later proposed Gander–Dunnage terranes (zones) of Williams *et al.* (1989). The radiometric age-dates obtained from the Grey River and Cinq Cerf units led to the assignment of these units to a Precambrian terrane affiliated with either the late Precambrian Avalon Zone of eastern Newfoundland (Dunning and O'Brien, 1989; Keppie and Dallmeyer, 1989) or with the

Bras d'Or Terrane of Cape Breton Island (Loncarevic *et al.*, 1989; Barr and Raeside, 1989; Dunning *et al.*, 1990; Figure 3). Consequently, the Ramea Islands would lie within one of these two Precambrian terranes.

Lithological correlations between the island of Ramea and the Bras d'Or and Mira terranes of Cape Breton Island are apparently lacking. Mylonitic granite cut by massive biotite granites are unknown within either the Bras d'Or and Mira terranes or in the Avalon Zone in Newfoundland. The only apparent lithological correlative in the Cape Breton Island terranes is the Neils Harbour Gneiss, which has an assigned age of 403 ± 3 Ma (Dunning *et al.*, 1990). This unit is correlated with the coarsely porphyritic Cameron Brook Granodiorite, dated at 402 ± 3 Ma, (Dunning *et al.*, 1990). However, unlike the Ramea mylonite, these units are not cut by massive granites. The Neils Harbour Gneiss and the Cameron Brook Granodiorite more closely resemble parts of the Burgeo Intrusive Suite.

The mylonitic granite in Ramea (Unit 2, Figure 2) is a possible affiliate with mylonitic granite southwest of Devil Bay (Figure 1). Correlation of these two units implies 60 km of movement along an assumed shear zone south of the enclave to restore these components to their inferred original positions. The relatively old, mylonitic, porphyritic biotite granites are a characteristic of the eastern margin of the Gander Zone, e.g., the Lockers Bay and Cape Freels granites of northeastern Newfoundland. As in Ramea, these mylonitic granites are cut by a variety of massive granites. Correlation of these sequences of intrusion would imply that a component of the Gander Zone lies south of the Precambrian Avalon or Bras d'Or terranes and that a significant tectonic boundary may separate the Ramea Islands from these terranes.

The presence of a terrane boundary is also supported by the position of the highly evolved, posttectonic Devonian granites such as the François, Chetwynd and Ackley granites of southern Newfoundland and the posttectonic, leucocratic biotite granite of Ramea. These granites are not zone specific but they are concentrated near the boundaries of the Avalon Zone with the Gander and Dunnage zones. Carboniferous granites of this type (e.g., Pé-Piper *et al.*, 1989) are common at the southern edge of the Avalon Terrane in northern Nova Scotia. Similar granites in southern New Brunswick lie just to the north of the exposed limit of the Avalon Zone and north of the Belleisle Fault (e.g., McLeod *et al.*, 1988). It appears that this type of granite is a characteristic of major tectonic boundaries.

The emplacement of massive gabbro and diabase intrusions in the Ramea Islands, along the south coast and at Penguin Islands, may have been focused by a significant shear zone. The east-trending aeromagnetic anomalies, which are interpreted to indicate the southern margin of the Burgeo Intrusive Suite, may also mark the position of a shear zone between the Grey River enclave and the Ramea Islands.

CONCLUSIONS

The foliated to mylonitic biotite granites cut by massive granites found in Ramea are also a characteristic feature of the eastern margin of the Gander Zone. The Ramea Islands possibly represent a fragment of Gander terrane separated from the main Gander Zone by the Grey River enclave. There are no definitive correlations of the early Ramea granitoids (Units 1 to 4) with the enclave, Cinq Cerf units, the Newfoundland Avalon Zone or with the Cape Breton Island Bras d'Or or Mira terranes.

Possible dextral shear indicators in the mylonitic granite at Ramea and its tentative correlation with a similar unit to the east-northeast, near Devil Bay, implies 60 km of dextral movement. Radiometric dating of the main units in Ramea could resolve the problems of correlation. This brief survey has indicated that the geology of the Ramea Islands is more complex than previously reported and should be considered when defining the boundaries of tectonostratigraphic zones.

ACKNOWLEDGMENTS

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REFERENCES

Bahyrycz, G.S.
1957: Geology of the Grey River area, Newfoundland. Unpublished M.Sc. thesis, McGill University, Montreal, 101 pages.

Barr, S.M. and Raeside, R.P.
1986: Pre-Carboniferous tectonostratigraphic subdivisions of Cape Breton Island, Nova Scotia. Maritime Sediments and Atlantic Geology, Volume 22, pages 252-263.

1989: Tectono-stratigraphic terranes in Cape Breton Island, Nova Scotia: Implications for the configuration of the northern Appalachian orogen. Geology, Volume 17, pages 822-825.

Blackwood, R.F.
1985: Geology of the Grey River area, southwest coast of Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 153-164. *Also in* Current Research, Part B. Geological Survey of Canada Paper 85-1B, pages 617-629.

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. (Compilers)
1990: Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-01.

Dickson, W.L., Blackwood, R.F., Delaney, P.W. and Poole, J.
1984: La Hune (11P/10) map area. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 8463.

Dickson, W.L., Delaney, P.W. and Poole, J.
1985: Geology of the Burgeo Granite and associated rocks in the Ramea (11P/11) and La Hune (11P/10) map areas, southern Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division Report 85-1, pages 137-144.

Dickson, W.L., Hayes, J.P., O'Brien, S.J. and Tuach, J.
1988: Late Devonian—early Carboniferous, high-silica granites in southern Newfoundland. *In* Geological Association of Canada—Mineralogical Association of Canada—Canadian Society of Petroleum Geologists, Program with Abstracts, Volume 13, page A32.

Dickson, W.L., O'Brien, S.J. and Hayes, J.P.
1989: Aspects of the mid-Paleozoic magmatic history of the south-central Hermitage Flexure area, Newfoundland. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 81-95.

Dunning, G.R. and O'Brien, S.J.
1989: Late Proterozoic—early Paleozoic crust in the Hermitage flexure, Newfoundland Appalachians: U/Pb ages and tectonic significance. Geology, Volume 17, pages 548-551.

Dunning, G.R., Barr, S.M., Raeside, R.P. and Jamieson, R.A.
1990: U—Pb zircon, titanite, and monazite ages in the Bras d'Or and Aspy terranes of Cape Breton Island, Nova Scotia: Implications for igneous and metamorphic history. Geological Society of America Bulletin, Volume 102, pages 322-330.

Dunning, G.R., Krogh, T.E., O'Brien, S.J., Colman-Sadd, S.P. and O'Neill, P.
1988: Geochronologic framework for the Central Mobile belt in southern Newfoundland and the importance of Silurian orogeny. *In* Geological Association of Canada—Mineralogical Association of Canada—Canadian Society of Petroleum Geologists, Program with Abstracts, Volume 13, page A34.

Dunning, G.R., O'Brien, S.J., Colman-Sadd, S.P., Blackwood, R.F., O'Neill, P.P., Dickson, W.L. and Krogh, T.E.
1990: Silurian orogeny in the Newfoundland Appalachians. Journal of Geology, Volume 98, pages 89-913.

Geological Survey of Canada
1986: Ramea, Newfoundland. Aeromagnetic total-field map. Geological Survey of Canada, Map 9649G.

Higgins, N.C., Halliday, A.N. and Mitchell, J.G.
1990: Age of a K-feldspar megacrystic granite from the Burgeo Intrusive Suite, and timing of tungsten mineralization at Grey River, southern Newfoundland. Canadian Journal of Earth Sciences, Volume 27, pages 893-902.

Higgins, N.C. and Smyth, W.R.
1980: Geology of the Grey River area—regional summary. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 80-1, pages 89-92.

Howarth, R.T. and Lefort, J.P.
1979: Geophysical evidence for the extent of the Avalon zone in Atlantic Canada. Canadian Journal of Earth Sciences, Volume 16, pages 552-567.

Keppie, J.D.
1990: Tectono-stratigraphic terranes in Cape Breton Island, Nova Scotia: Implications for the configuration of the northern Appalachian orogen—Comment. Geology, Volume 18, pages 669-670.

Keppie, J.D. and Dallmeyer, R.D.
1989: Tectonic map of pre-Mesozoic terranes in circum-Atlantic Orogens. Nova Scotia Department of Mines and Energy, Halifax, Nova Scotia.

Keppie, J.D., Dallmeyer, R.D. and Murphy, J.B.
1990: Tectonic implications of ^{40}Ar/^{39}Ar hornblende ages from late Proterozoic-Cambrian plutons in the Avalon Composite Terrane, Nova Scotia. Geological Society of America Bulletin, Volume 102, pages 516-528.

Loncarevic, B.D., Barr, S.M., Raeside, R.P., Keen, C.E. and Marillier, F.
1989: Northeastern extension and crustal expression of terranes from Cape Breton Island, Nova Scotia, based on geophysical data. Canadian Journal of Earth Sciences, Volume 26, pages 2255-2267.

Marillier, F., Keen, C.E., Stockmal, G.S., Quinlan, G., Williams, H., Colman-Sadd, S.P. and O'Brien, S.J.
1989: Crustal structure and surface zonation of the Canadian Appalachians: implications of deep seismic reflection data. Canadian Journal of Earth Sciences, Volume 26, pages 305-321.

McLeod, M.J., Taylor, R.P. and Lux, D.R.
1988: Geology, ^{40}Ar/^{39}Ar geochronology and Sn—W—Mo—bearing sheeted veins of the Mount Douglas Granite, southwestern New Brunswick. Canadian Institute of Mining and Metallurgy Bulletin, Volume 81, pages 70-77.

O'Brien, B.H. and O'Brien, S.J.
1990: Re-investigation and re-interpretation of the Silurian La Poile Group of southwestern Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 305-316.

O'Brien, S.J. and Dickson, W.L.
1986: Burgeo (11P), Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 86-32.

O'Brien, S.J. and Tomlin, S.L.
1985: Geology of the Burgeo map area (11P/12), southwest Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 114-123.

O'Brien, S.J., Dickson, W.L. and Blackwood, R.F.
1986: Geology of the central portion of the Hermitage Flexure area, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 189-208.

Pé-Piper, G., Cormier, R.F. and Piper, D.J.W.
1989: The age and significance of Carboniferous plutons of the western Cobequid Highlands, Nova Scotia. Canadian Journal of Earth Sciences, Volume 26, pages 1297-1307.

Piasecki, M.A.J., Williams, H. and Colman-Sadd, S.P.
1990: Tectonic relationships along the Meelpaeg, Burgeo and Burlington Lithoprobe transects in Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 327-339.

Stewart, P.W. and Dunning, G.R
1990: The La Poile Group, the Hope Brook gold mine and geochronology. Abstracts, Atlantic Geoscience Society, 1990 Symposium, Wolfville, Nova Scotia. *In* Atlantic Geology, Volume 26, pages 187-188.

Williams, H.
1971: Burgeo (east half), Newfoundland. Geological Survey of Canada, map 1280A.

Williams, H., Colman-Sadd, S.P. and Swinden, H.S.
1988: Tectonic-stratigraphic subdivisions of central Newfoundland. *In* Current Research, Part B. Geological Survey of Canada, Paper 88-1B, pages 91-98.

Williams, H., Dickson, W.L., Currie, K.L., Hayes, J.P. and Tuach, J.
1989: Preliminary report on a classification of Newfoundland granitoid rocks and their relations to tectonostratigraphic zones and lower crustal blocks. *In* Current Research, Part B, Geological Survey of Canada Paper 89-1B, pages 47-53.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 97-107

THE STRUCTURAL EVOLUTION OF THE NORTHERN SEGMENT OF THE DUNNAGE ZONE–GANDER ZONE BOUNDARY, NEWFOUNDLAND

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ABSTRACT

Detailed mapping and structural analyses including investigation of sense-of-shear indicators, have been carried out along the Dunnage–Gander zone boundary. The portion of the boundary studied separates the Exploits Subzone from the Gander Lake Subzone between Gander Lake to the south and Musgrave Harbour to the north.

Deformation events recorded by structures along and adjacent to the boundary are divided into three groups. The oldest structures, for which kinematic indicators exist, developed through ductile strike-slip and oblique-slip motion. Dextral predated sinistral displacement; however, more than two episodes of ductile strike-slip and oblique-slip movement may have occurred. Structural features in rocks along the shores of Ragged Harbour indicate that some of the movement was contemporaneous with Siluro-Devonian plutonism.

Low-angle normal motion resulted in the development of mylonite, which overprints steeply dipping fabrics. The relative timing of low-angle normal ductile shear and ductile-brittle to brittle faulting is unknown. The latter postdates the cooling of a Devonian granite, but is otherwise unconstrained in age. Notable among the southeast faults are north-trending normal faults (west-side-down) and the most common west- to northwest-trending dextral strike-slip faults. Both sets may be related to the Atlantic opening.

It is here suggested that the present form of the Exploits–Gander Lake subzone boundary is largely the result of at least two episodes of strike-slip and oblique-slip motion.

INTRODUCTION

The Dunnage Zone has been divided into the geologically distinct Notre Dame and Exploits subzones (Williams, H. *et al.*, 1988). The Gander Zone has been separated into the Mt. Cormack, Meelpaeg and Gander Lake subzones (Williams, H. *et al.*, 1988). The Exploits–Gander Lake subzone boundary, with which this study is concerned, represents the easternmost Dunnage–Gander zone boundary. It is most clearly defined to the north, where much of the steeply dipping contact is bordered, on the Exploits side, by the Gander River complex (GRC; O'Neill and Blackwood, 1989: formerly the Gander River Ultramafic Belt of Jenness, 1958; Blackwood, 1978, 1982). Where present, the GRC is imbricated with the Weir's Pond Formation, the basal division of the Davidsville Group of the Exploits Subzone (O'Neill and Blackwood, 1989), and is juxtaposed against the Gander Group of the Gander Lake Subzone (Figure 1).

Interpretations of the structural history of the Exploits–Gander Lake subzone boundary vary. Kennedy and McGonigal (1972) proposed that the Davidsville Group was deposited unconformably on the deformed and metamorphosed Gander Group, and cited as evidence the presence of detrital biotite and garnet, and mafic schist and psammite fragments in basal conglomerate of the Davidsville Group. Uzuakpunwa (1973) examined the Gander and Davidsville groups and associated igneous rocks in the Ladle Cove–Ragged Harbour–Island Pond area. He concluded that the Gander Group had acquired a composite fabric before juxtaposition against the Davidsville Group, and noted that the metamorphic fragments in the melange of the Davidsville Group have folds, which predate incorporation of the fragments. Also, he considered the melange, which contains blocks of serpentinized dunite breccia, mafic pillow lava and hornblende gabbro, to be tectonic, and to have formed during thrusting of the Davidsville Group onto the Gander Group. The two groups were interpreted as being separated by either a melange, an ultramafic belt or a fault, and he mapped a narrow band of intensely foliated phyllite in the Ragged Harbour River area.

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[1] Lithoprobe Contribution Number 205

[2] Newfoundland Mapping Section

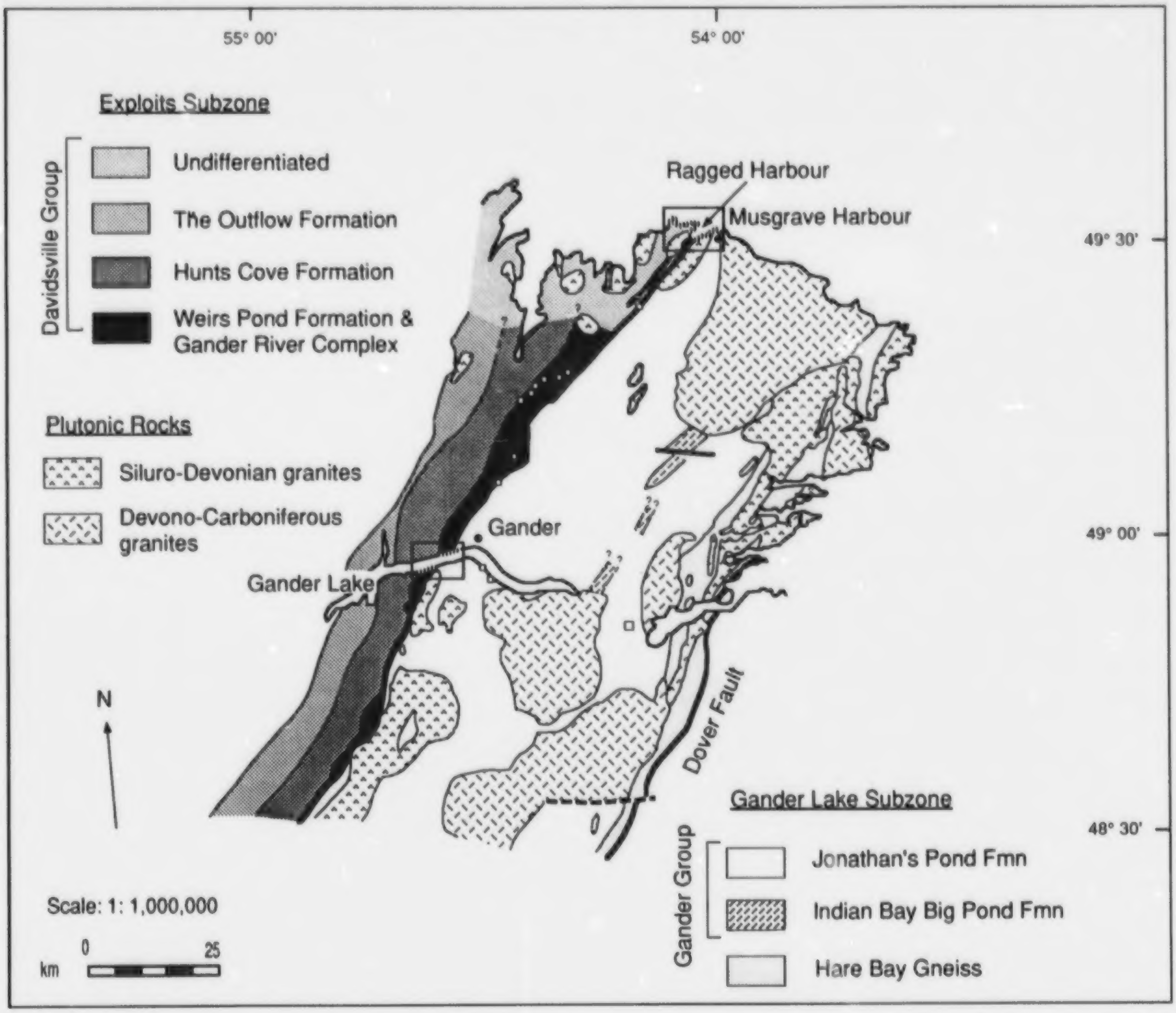

55° 00'
54° 00'
49° 30'
49° 00'
48° 30'
Exploits Subzone
Davidsville Group
Undifferentiated
The Outflow Formation
Hunts Cove Formation
Weirs Pond Formation & Gander River Complex
Plutonic Rocks
Siluro-Devonian granites
Devono-Carboniferous granites
Ragged Harbour
Musgrave Harbour
Gander
Gander Lake
Dover Fault
N
Scale: 1: 1,000,000
0
25
km
Gander Lake Subzone
Gander Group
Jonathan's Pond Fmn
Indian Bay Big Pond Fmn
Hare Bay Gneiss

Figure 1. *Simplified map of the northern Dunnage–Gander zone boundary. Detailed structural information was collected from areas indicated by small squares and traverses marked by striped lines (within boxes).*

The two very different interpretations of the boundary as an unconformity and as a tectonic contact also appear in more recent literature. The Carmanville area was the focus of a number of studies (Currie and Pajari, 1977; Pickerill *et al.*, 1978, 1981; Pajari and Currie, 1978; Pajari *et al.*, 1979 and Currie *et al.*, 1979, 1980a, b). Currie and Pajari (1977) concluded that the basal part of the Davidsville Group, near Carmanville, forms part of an allochthonous sheet, spatially associated with an olistostromal melange at its base. Pajari *et al.* (1979) interpreted this melange, which they described as containing granule- to kilometre-size fragments in a shale matrix, to be ophiolitic. The shale matrix has been shown since, in places, to consist of shale clasts, and at least some of the olistostrome horizons mapped by Pajari *et al.* (1979) are clast-supported conglomerates (Williams, 1983). Pajari *et al.* (1979) suggested that olistostrome formation may have commenced as early as the Arenig and that fragments in the olistostrome were derived mainly from early Paleozoic oceanic crust and volcanic rocks (now represented by the GRC), which Pajari *et al.* (1979) interpreted as having been obducted eastward over the eastern continental margin of the Iapetus Ocean. Currie and Pajari (1977) also describe rocks exposed along Ragged Harbour River that contain a mylonitic foliation. They note that complex relict fold structures in rocks of the Gander Group do not occur in the Davidsville Group, 'possibly indicating a structural discontinuity between Gander and Davidsville sequences'.

Blackwood (1978) noted that the nature of the contact between the Davidsville and Gander groups is enigmatic where the GRC is present. Where the GRC is absent, near Island Pond in the Carmanville area and south of Gander Lake, the contact relationships between the Davidsville and Gander groups have been interpreted as conformable (Currie and Pajari, 1977; Blackwood, 1982). Blackwood (1982) suggested that the GRC was nonconformably overlain and bounded to the west by the Davidsville Group, which he interpreted as a submarine fan with distal deposits in the east and proximal in the west. Spatially restricted proximal conglomerates, which occur in the basal Davidsville Group, were, in his model, a product of erosion of ophiolitic basement, which was uplifted along wrench–transform faults. He proposed (in contrast to Currie *et al.*, 1979) that this initial uplift was due to 'oceanic disturbances' (rather than obduction) and interpreted the faulted contact between the GRC and the Gander Group as a major west-dipping thrust, along which the complex was emplaced above the Gander Group during later, regional deformation. Pajari *et al.* (1979) also described the contact between the GRC and the Gander Group as a fault.

Piasecki (1988), based on preliminary work northeast of Weir's Pond, suggested that the contact between the Gander and Davidsville groups is defined by a kilometre-wide mylonite zone, in which kinematic indicators imply south- to southwest-directed movements of the Davidsville Group over the Gander Group.

Research on the nature of the Exploits–Gander Lake subzone boundary, by one of us (LBG), was undertaken as part of a Lithoprobe East project to understand the structural evolution of the eastern and western margins of the Dunnage Zone. Detailed mapping and structural analyses of key areas, including investigation of sense-of-shear indicators, have been carried out along the north and south shores of Gander Lake and along the north coast (Figure 1). Structural information has also been collected from a number of points within, adjacent to, and to the east of the boundary zone (Figure 1). Preliminary results from ongoing analyses of microstructures and textures are also presented.

STRUCTURAL HISTORY

The events recorded by structures along the Exploits–Gander Lake subzone boundary in the study area are:

1) strike-slip and oblique-slip motion, with both dextral and sinistral displacement; contemporaneous with and post-dating Siluro-Devonian plutonism;

2) locally developed low-angle normal movement; and

3) high- to moderate-angle brittle-ductile to brittle faulting; postdates Devonian plutonism.

More detailed discussion of each of the main deformation events follows.

STRIKE-SLIP AND OBLIQUE-SLIP MOTION

Within the study area, the Exploits–Gander Lake subzone boundary and adjacent structures generally dip steeply to the northwest and are locally vertical. Sense-of-shear indicators generally indicate strike-slip or oblique-slip movement and show that the boundary zone has experienced both sinistral and dextral strike-slip displacement.

Our use of stratigraphy of rocks along and adjacent to the boundary will follow O'Neill and Blackwood (1989). From south to north in the study area (Figure 1), the following observations have been made.

On the south shore of Gander Lake, the boundary zone lies within a region where rocks are locally highly strained; although strain is distributed heterogeneously within this region, we will refer to it as a high-strain zone. To the west of the high-strain zone, rocks of the Davidsville Group display a moderately developed, moderately westward-dipping foliation and locally exhibit a poorly developed, down-dip mineral lineation. A steeply to moderately west-dipping foliation, into which the cleavage appears to be transposed, is developed eastward toward the boundary, within the high-strain zone (Figure 2, solid circles). This foliation generally contains a mineral lineation, which is locally defined by the long axes of stretched pebbles (Figure 2, solid squares). Apparent strain partitioning among different rock types in the Davidsville Group results in a variation in orientation of this stretching lineation, which on average plunges moderately to the north, but may plunge shallowly or steeply. Locally, two mineral lineations are present, and the steeper is inferred to be a relic of the older fabric. Sense-of-shear indicators are confined to deformed quartz veins, which do not record a consistent movement sense. Offset of quartz veins in this region of the Davidsville Group, generally indicates a strike-slip component of movement that is sinistral. The dip-slip component is determined to be west-side-up (reverse) in an area where the lineation has a northerly plunge and west-side-down (normal) in an outcrop where the mineral lineation plunges southward. In one location, a dextral strike-slip component is indicated. In an other locality, where the lineation is nearly down-dip, deformation of a quartz vein indicates normal motion. These apparently contradictory observations suggest the possibility of both multiple episodes of deformation and multiple generations of quartz veins. Microstructural and textural analyses, necessary to determine the significance of these complex field observations, is in progress. Similarly oriented foliations and lineations are found within rocks of the Gander Group adjacent to the boundary (Figure 2, solid circles and squares). Isoclinal, intrafolial folds in an older foliation, which are present in these rocks are however, absent in the Davidsville Group. This suggests that the high-strain zone overprinted Gander Group rocks that were already very well foliated. As mentioned previously, the high-strain zone is heterogeneous. The fabric within an area of lower strain (Figure 2, open circles and squares) is similar to that in adjacent, more strongly deformed rocks, though it dips less steeply.

On the north shore of Gander Lake, metamorphic rocks of the Jonathans Pond Formation are separated from ultramafic rocks of the GRC by a break in outcrop. The ultramafic rocks are cut by numerous slickensided surfaces

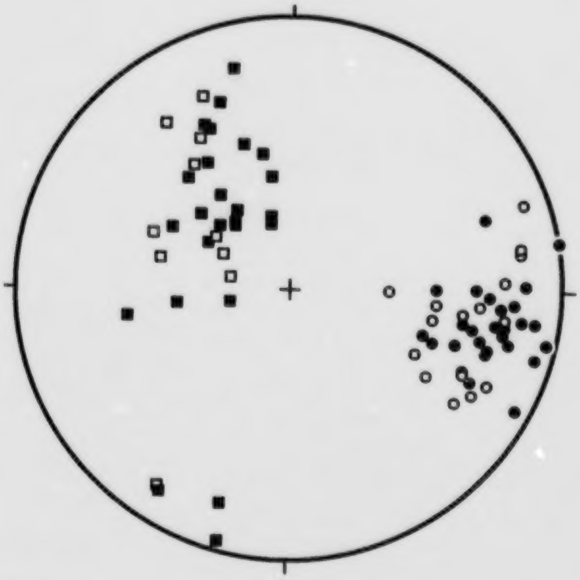


Figure 2. *Lower hemisphere, equal-area plot of structural elements, south shore of Gander Lake. Circles represent poles to foliation; squares are lineations. Black fill = fabric in highly strained rocks of the Davidsville and Gander groups and white fill = fabric of less deformed rocks of the Davidsville Group. See text for further explanation.*

and are typically non-foliated. In contrast, rocks of the Jonathans Pond Formation exposed closest to the boundary exhibit a well-developed, moderately westerly dipping foliation and nearly down-dip mineral lineation. Preliminary petrographic study of a rock sample from this part of the Jonathans Pond Formation, shows that the foliation and associated extensional lineation formed during normal shear with a small sinistral component of motion. This movement sense is indicated by the orientation of shear bands relative to C-surfaces and by a deformed carbonate vein. Whether normal shear is coupled with the strike-slip and oblique-slip movements recorded elsewhere along the boundary, or is related to younger extension (see following section), is presently unknown.

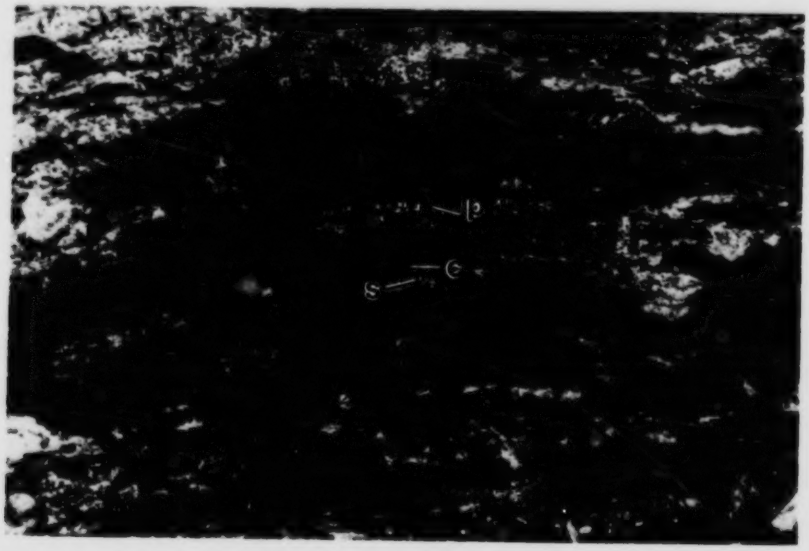
Within the Weir's Pond map area, high-strain zones are developed in both the GRC and the Weir's Pond Formation. In both a sheared trondhjemite-rich conglomerate in the west and a deformed gabbro farther east, kinematic indicators record dextral strike-slip movement. The deformed conglomerate occurs within a high-strain zone that extends a minimum of 0.75 km along strike; ultramafic rocks of the GRC are also highly deformed within this zone. Sense-of-shear indicators in both the gabbro (Figure 3a) and the conglomerate include S- and C-surfaces (cf. Berthe *et al.*, 1979) and C and C' (shear band) surfaces. A subhorizontal stretching lineation is found within the C-surfaces (Figure 3b). S-surfaces in the gabbro were later folded, indicating reactivation of the C-surfaces during sinistral strike-slip motion (Figure 3c). Therefore, an episode of sinistral strike-slip motion postdated dextral strike-slip motion; the folds indicate only a small amount of sinistral displacement in this area.

The GRC is absent along part of the boundary in the Carmanville map area and the Davidsville Group is in direct contact with the Gander Group. Preliminary investigation of this portion of the boundary indicates that a moderately to steeply northwest-dipping foliation is developed in rocks of both groups (Figure 4). A shallowly plunging mineral lineation (Figure 4) is present in the plane of this foliation within quartz-rich rocks of the Gander Group only. Well-developed shear bands in pelitic rocks of the Gander Group and a strongly deformed quartz vein in the Davidsville Group both record sinistral strike-slip motion. The shallow southwest plunge of the locally developed mineral lineation suggests the possibility of a small west-side-down dip-slip component to the movement. The boundary between the Davidsville and Gander groups, where the GRC is absent, is clearly tectonic.

Rocks on the eastern and western shores of Ragged Harbour, as well as in areas in adjacent Musgrave Harbour, exhibit evidence of several deformation events, some of which were contemporary with granitic plutonism. Metasedimentary rocks, migmatites and leucocratic granites are intimately intermingled and deformed. The metasedimentary rocks in this area have experienced a higher grade of metamorphism than elsewhere along the northern Exploits–Gander Lake subzone boundary. Biotite is ubiquitous and garnet is common; andalusite and sillimanite are found locally on the northwest shore and sillimanite is common on the northeast shore of Ragged Harbour. Some xenoliths in highly deformed granite in Musgrave Harbour contain kyanite, which is overprinted by sillimanite. Kyanite has also been found near Wing Pond, in the Gander Lake Subzone, within a high-strain zone (O'Neill and Lux, 1989) that extends at least as far south as Square Pond (see O'Neill, *this volume*). Andalusite is common within the Wing Pond Shear Zone (Plate 1), which is also locally associated with leucocratic granite and contains evidence of oblique-slip movement.

The earliest phases of deformation, for which clear evidence is present in the Ragged Harbour and Musgrave

Figure 3. *High-strain zones in the GRC; a) View is parallel to the lineation and at right angles to the foliation. The orientation of S-relative to C-surfaces (marked) indicate dextral displacement. Note extended plagioclase porphyroclasts (p). Dark zones parallel to C-surfaces are ultramylonite; b) Lower hemisphere, equal-area projection: circles are poles to foliation and squares are lineations. Black fill = fabric in deformed gabbro; white fill = fabric in deformed trondhjemite and ultramafic rock; c) Viewed parallel to the lineation and at right angles to the foliation. Folds with sinistral asymmetry (f) are developed mainly in S-surfaces (S- and C-surfaces are marked).*



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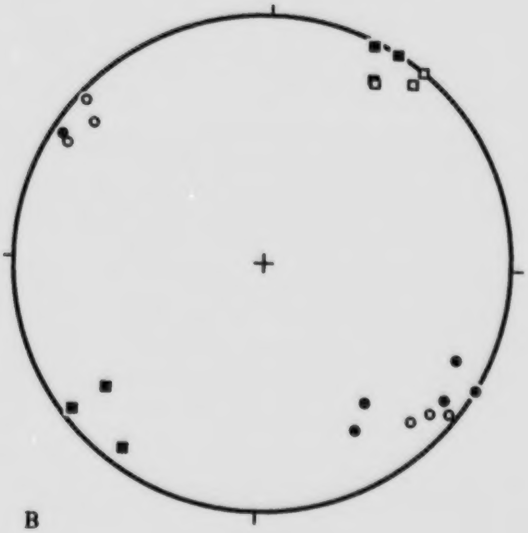

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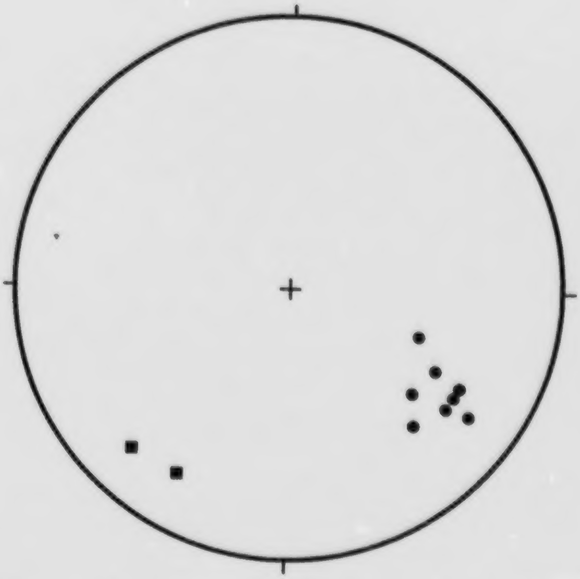

Figure 4. *Lower hemisphere, equal-area projection of fabric elements at Gander–Davidsville group contact. Poles to foliation are represented by circles; lineations are plotted as squares.*

Plate 1. *High-strain zone near Square Pond, showing folded andalusite porphyroblast (a) and typical dextral asymmetry of folded quartz vein (q). Viewed at right angles to foliation and ~45° from lineation.*

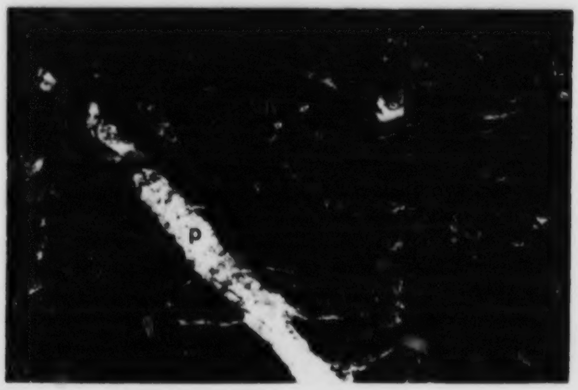

Plate 2. *Shear bands (sb) developed in migmatite near Musgravetown Harbour indicate a sinistral component of shear. Viewed ~45° from lineation (which plunges to the right in the photograph) and at right angles to foliation. Segregation of leucosomes along shear bands is evident (lighter zones at 'l' to the right of sb). Crosscutting pegmatite vein (P) is undeformed.*

Harbour area, were strike-slip and oblique-slip movements resulting in the development of steeply dipping foliations and subhorizontal to moderately plunging mineral lineations. Steep mineral lineations are found locally. Evidence for synplutonic deformation includes leucocratic granite intrusions exhibiting parallel magmatic and tectonic fabrics and multiple phases of intrusion, with granites of different ages showing variably developed, but consistently oriented foliations. Migmatites near Musgrave Harbour contain leucosome segregations along shear-band boundaries (Plate 2); the shear bands indicate oblique-slip movement with sinistral and reverse components. Sense-of-shear indicators elsewhere include offset veins, shear bands and drag folds (e.g., Plate 3). Sinistral strike-slip motion with virtually no component of dip-slip movement is recorded at Ragged Point, where a nearly vertical foliation contains a subhorizontal mineral lineation (Plate 3). Kinematic indicators at several localities within the White Point Complex of Currie *et al.* (1980b), along the east and west shores of Ragged Harbour, indicate dextral strike-slip motion and oblique movement with a component of dextral displacement. Overprinting relationships confirm the observation made to the south that sinistral strike-slip motion postdated dextral movement along the Exploits–Gander Lake subzone boundary.

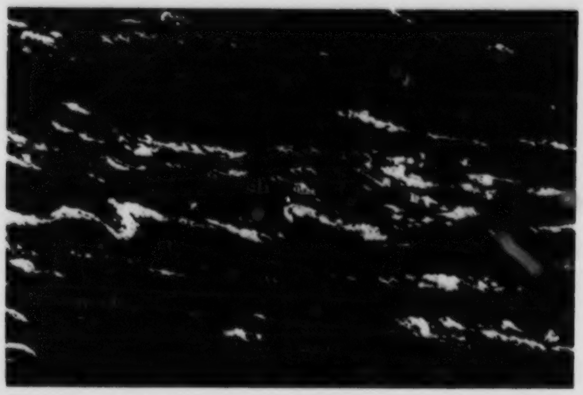

Plate 3. *Mylonite at Ragged Point is viewed parallel to lineation and at right angles to foliation. Asymmetric drag folds in granite veins (f) and movement on shear bands (sb) indicate sinistral shear.*

LOW-ANGLE NORMAL MOVEMENT

On the east shore of Ragged Harbour, south of the town of Ragged Harbour, evidence of ductile normal movement with a variable component of sinistral motion is preserved in granite of the White Point Complex. Deformation of leucocratic granite has resulted in the development of C-surfaces that strike north-northeast and dip, on average, 45° to the east. S-surfaces indicate normal to oblique displacement (Figure 5). This fabric locally overprints the steeply dipping foliation typical of the area (see above). In the area of overprinting, the younger foliation is broadly folded, suggesting a dome shape, which results in some scatter in the orientations of poles to foliations (Figure 5). The relative age of this low-angle normal movement with respect to faults in the area is unknown; emplacement and cooling ages of the granite mylonite would provide constraints on the timing of this deformation episode.

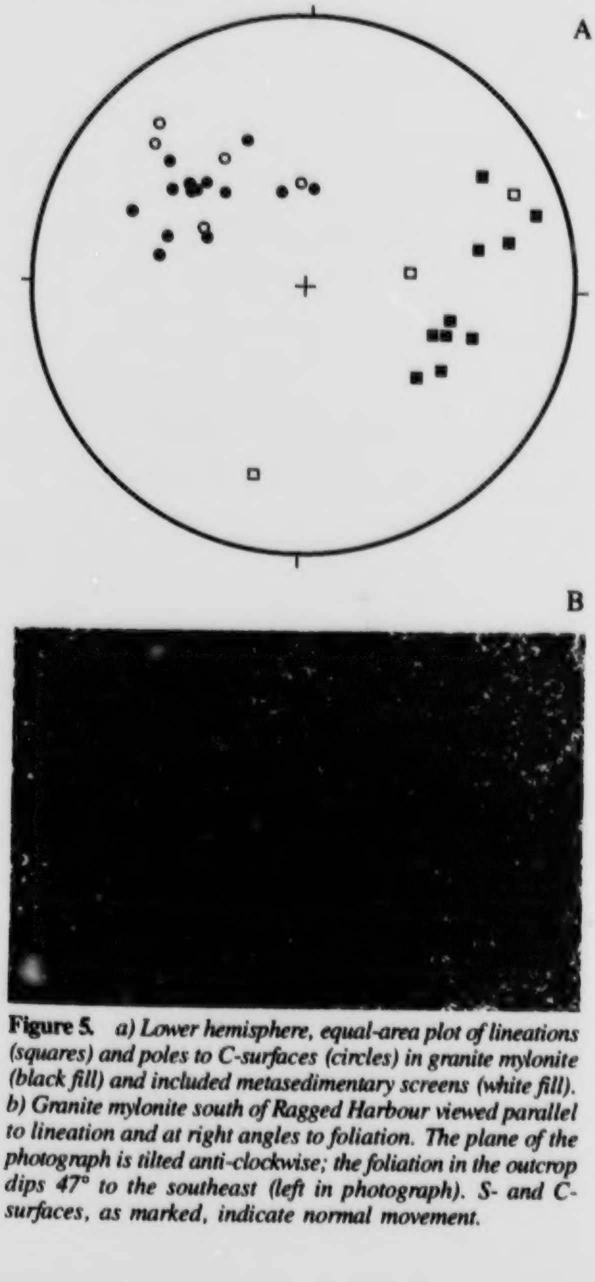

Figure 5. *a) Lower hemisphere, equal-area plot of lineations (squares) and poles to C-surfaces (circles) in granite mylonite (black fill) and included metasedimentary screens (white fill). b) Granite mylonite south of Ragged Harbour viewed parallel to lineation and at right angles to foliation. The plane of the photograph is tilted anti-clockwise; the foliation in the outcrop dips 47° to the southeast (left in photograph). S- and C-surfaces, as marked, indicate normal movement.*

Extension that may be related to low-angle normal motion is recorded elsewhere by a locally developed, shallowly dipping cleavage, along which older foliations are either flattened or offset in a normal sense.

FAULTS

Moderate- to high-angle brittle-ductile to brittle faults crosscut fabrics developed during strike-slip and oblique-slip motions. They occur in west-, northwest-, north- and northeast-trending sets. West-trending faults are the most common; the others appear to occur in roughly equal numbers. The offset along most northeast-trending faults cannot be determined. For the purposes of discussion, the remaining faults will be grouped into roughly northerly trending and west- to northwest-trending sets. Both usually contain multiple sets of slickenside striae and are often associated with quartz fibres. If more than one set of slickenside striae is present, one is generally shallowly plunging and one is commonly steeply plunging, indicating the importance of both strike-slip and dip-slip motion along the faults.

Offset along these faults is commonly difficult to ascertain. Where it is possible to elucidate sense of movement, the northerly trending faults are commonly normal faults and the west- to northwest-trending faults are typically dextral strike-slip faults. However, the relations mentioned above indicate that many of these faults have been reactivated at least once in their history. West- to northwest-trending sinistral strike-slip and normal faults, and north-trending sinistral strike-slip and reverse faults, have been noted. Many of these faults may not be exposed because these fault zones are easily eroded and the outcrop in this region is so poor. It is also important to note that these faults are much more common in the southern portion of the area studied; this may be because the structural level exposed along the north coast is much deeper than that farther south (as indicated by the high-grade metamorphic rocks and migmatites that outcrop along Ragged Harbour).

The northerly trending normal faults and west- to northwest-trending dextral faults have a definite influence on the present distribution of rock units.

Northerly Trending Normal Faults

The normal faults are distinctive in that they commonly dip steeply (locally are vertical) and displacement may be sufficient to juxtapose rocks of substantially different metamorphic grade. The best exposed example is located at Ladle Point, on the east side of Aspen Cove. The fault surface is nearly vertical (dipping westward), is locally associated with a quartz vein and contains nearly down-dip slickenside striae. The sense of movement on this fault is west-side down. Rocks that are deformed, but exhibit no macroscopically visible metamorphic minerals and preserve primary structures, are dropped down next to their andalusite-bearing equivalents along this fault. Northerly trending normal faults indicate east-west extension, which may be associated with Atlantic opening.

West- to Northwest-Trending Dextral Strike-Slip Faults

Dextral strike-slip motion along west- to northwest-trending faults affected the Devonian Deadmans Bay Granite near the fish plant at Musgrave Harbour. Zones of brittle-ductile foliation (Plate 4), a few metres wide, become brittle toward the centre. These zones crosscut a magmatic foliation, indicating that this phase of deformation postdated cooling of the pluton and was therefore Devonian or younger in age. Northerly trending aplite dykes crosscut the brittle-ductile foliation and are slightly dextrally offset by the centrally located brittle faults. This may indicate a substantial temporal difference between brittle-ductile and brittle deformation, or that initially brittle-ductile deformation became progressively brittle and more localized in space. The normal fault at Ladle Point (mentioned above) is also dextrally offset by a high-angle, west-trending fault containing well-developed sub-horizontal slickenside striae. The Gander Lake fault (McGonigal, 1973) also dextrally offsets the GRC. Although it was described previously as a normal fault, offset of metasedimentary rocks of the Davidsville Group along a lake-parallel fault on the south shore of Gander Lake suggests that it belongs to this class of faults. West and northwest geographical trends (e.g., the orientation of the north coast and the trend of bays on the eastern margin of the Gander Lake Subzone) probably reflect this common fault attitude. Apparent offset of geological features may also be explained by these faults (as suggested by the heavy dashed line in Figure 1).

Plate 4. *Deformed granite viewed parallel to lineation and at right angles to brittle-ductile foliation in Deadmans Bay pluton, near fish plant at Musgrave Harbour. Direction of slip on fracture in feldspar (arrows), interpreted as movement along a shear band, suggests dextral displacement on main foliation surfaces.*

These dextral strike-slip faults are similar in trend and character to faults described in southern New Brunswick (Leger and Williams, 1986), northern Newfoundland (Williams, P. *et al.*, 1988), Nova Scotia (Williams and Hy, 1990) and throughout eastern Canada (Miller, 1990) and may similarly represent transfer faults associated with Atlantic opening.

Significance of High-Angle Faults

The brittle structures discussed here are important for two reasons. First, they can accomplish a significant amount of lateral and/or vertical shuffling of lithological units. Where there is a strong component of vertical displacement, this can result in dramatic lateral changes in metamorphic grade. Second, rotation of rocks along faults may result in significant changes in orientation of both bedding and foliation surfaces. For example, foliations in the Ragged Harbour area appear locally to be rotated into parallelism with brittle and brittle-ductile, dextral strike-slip faults.

Lithological boundaries are commonly faulted because of strong rheologic contrasts. Considering the poor outcrop in the area, the potential for rotation of structures across fault surfaces, and fault displacements, high-angle faults could mask or erase evidence of previous structural events.

PEGMATITE AND APLITE DYKES

Pegmatite dykes (Plate 2) on the east coast of Ragged Harbour crosscut the Siluro-Devonian leucocratic granitoids and fabrics developed during strike-slip and oblique-slip motion, and are generally little deformed to undeformed. As there is evidence for more than one episode of both intrusion and strike-slip motion, it is likely that there is more than one generation of pegmatite dykes. The dykes are deformed within the low-angle normal shear zone and are cut by the brittle faults.

Aplite dykes cut the Deadmans Bay Granite in Musgrave Harbour and are therefore younger than the pegmatite dykes. As mentioned previously, they truncate brittle-ductile foliation but are displaced along brittle faults. Where they are undeformed, or little deformed, both pegmatite and aplite dykes generally strike northerly and dip steeply. Although crosscutting relationships indicate that pegmatitic and aplitic dykes were intruded at different times, they both reflect approximately east-west extension. Dates on pegmatite and aplite emplacement would constrain the timing of the latest deformation in the area.

DISCUSSION

Boundaries between rocks of the Gander and Dunnage zones are geometrically diverse. In southern Newfoundland, the boundary is represented by the Bay d'Espoir shear zone (Colman-Sadd, 1980; Piasecki, 1988), which juxtaposes a thin sliver of probable Gander Zone rocks against rocks of Dunnage Zone affinity. Piasecki (1988) suggested that movement along the Bay d'Espoir shear zone involved sinistral strike-slip motion in zones of steep foliation coupled with west-southwest-directed movement of the Dunnage Zone over the Gander Zone in zones of shallow foliation. In south-central Newfoundland, the Mt. Cormack and Meelpaeg subzones form two tectonic windows through overlying

Exploits Subzone rocks and are locally bordered by Dunnage Zone ultramafic rocks (Colman-Sadd and Swinden, 1984; Williams, H. *et al.*, 1988). Colman-Sadd and Swinden (1984), Williams, H. *et al.* (1988) and Williams and Piasecki (1990) state that structural relationships along the Mt. Cormack and Meelpaeg subzone boundaries indicate that the Exploits Subzone, in part, overlies the Gander Zone and that these boundaries are fundamentally thrust surfaces. Colman-Sadd and Swinden (1984), Piasecki *et al.* (1990) and Williams and Piasecki (1990) suggest that later deformational events, including strike-slip and dip-slip motions, have modified structures in these areas.

In contrast to the other boundaries, there is no evidence along the Exploits–Gander Lake subzone boundary that the Exploits overlies the Gander Lake Subzone; the boundary generally dips steeply. The present structures and preserved sense-of-shear indicators chiefly record strike-slip and oblique-slip motion. A possible exception is the exposure of rocks adjacent to the Exploits–Gander Lake subzone boundary on the north shore of Gander Lake, where kinematic indicators observed in thin section, indicate normal motion, which may be related to younger extension. Zones which record oblique-slip motion may, as noted previously, contain evidence for a reverse component of movement. This is distinct from thrusting; with reverse motion along steeply dipping shear zones, transport of the hanging wall is limited by the thickness of the crust. Thrust movement, which by definition occurs within zones which dip 45° or less, allows transport of major allochthons for significant distances. No evidence for thrusting has been found. In addition, rocks of the Gander Group adjacent to the boundary, with the exception of those located within the high-strain zone in Ragged Harbour and those within the thermal aureoles of granites south of Gander Lake, have experienced greenschist-facies metamorphism, which is not what would be expected of rocks in the footwall of the major thrust sheet suggested by previous workers. Evidence from this study does support the conclusion of Uzuakpunwa (1973) and Piasecki (1988) that the Gander and Davidsville groups are in tectonic contact.

As noted by O'Neill and Knight (1988), aeromagnetic anomalies within the Gander Lake Subzone (e.g., the Ocean Pond Anomaly Belt of Miller, 1988) are oblique to the main trend of the Gander Lake–Exploits subzone boundary. The Ocean Pond Anomaly Belt appears to end at the Exploits–Gander Lake subzone boundary. This anomaly belt is spatially associated with a number of features at the surface, including the regional structural grain, the leucocratic Ocean Pond Granite and a small ultramafic body. Linear features within the anomaly belt (see Kilfoil, *this volume*) are spatially coincident with a strong physiographic lineament in which steeply dipping, highly strained rocks are locally exposed. These structural relationships and the consistently linear expression of the anomalies are more compatible with strike-slip and oblique-slip motion along steep shear zones than with thrusting. These observations suggest that the north-trending anomalies are associated with structures that developed during a different, perhaps earlier, deformation episode than that which formed the northeast-trending subzone boundary. In the eastern Gander Lake Subzone, the Wing Pond Shear Zone (See O'Neill, *this volume*) exhibits evidence of strike-slip motion and is coincident with an aeromagnetic anomaly and felsic, mafic and ultramafic bodies.

Shear zones partitioned into strike-slip and oblique-slip domains would transport rocks along strike and also bring material from depth toward the surface. The GRC clearly contains a basement component of ultramafic, gabbroic and trondhjemitic rocks. Some or all of the GRC could have been exhumed through oblique-slip motion. If portions of the GRC, and of the Weir's Pond Formation, were already at the surface when these shear zones initiated, then these rocks could have been placed in their present position through strike-slip motion. These shear zones may also explain the development of the aeromagnetic anomalies observed in the Gander Group. Zones of oblique-slip and strike-slip motion, localized along the present anomalies, could bring rocks up from depth within the Gander Lake Subzone in the same way as along the Exploits–Gander Lake subzone boundary. The presence of a few small ultramafic bodies along the anomalies suggests the possibility that the Gander Lake Subzone is floored by oceanic basement; however, few basement rocks were brought to the surface within these high-strain zones. This may reflect either a greater component of strike-slip movement within high-strain zones along the anomalies, or a smaller net displacement relative to the Exploits–Gander Lake subzone boundary.

Structural relationships in the area record coincident strike-slip and oblique-slip motions. Evidence in the Ragged Harbour area suggests that some strike-slip and oblique-slip motion was contemporaneous with Siluro-Devonian plutonism. Oblique-slip and strike-slip motion may have initiated prior to the Silurian, but the geochronologic data is limited and does not allow us to date the onset of this deformation.

CONCLUSIONS

The northern Exploits–Gander Lake subzone boundary records a complex deformation history. The boundary in its present form is largely the result of at least two episodes of strike-slip and oblique-slip motion; evidence of any previous structural event(s) has been obliterated. Siluro-Devonian granites and zones of high-grade metamorphic rocks are locally associated with high-strain zones (strike-slip and oblique-slip shear zones), indicating that intrusion and deformation were intimately related. This is further substantiated by the spatial association of the majority of Siluro-Devonian granites with the western and eastern boundaries of the Gander Lake Subzone, (see also Hanmer, 1981). Kyanite appears to be spatially restricted to these high-strain zones, suggesting significant dip-slip displacement in areas of oblique-slip motion. Low-angle normal motion, which postdates these two events, may have occurred during isostatic adjustment to a crust thickened by oblique-slip movement, or may be associated with Atlantic opening. Later high-angle faulting also influenced the pattern of isograds, spatial distribution of rock types, and orientation of structures. These faults may be associated with Atlantic opening.

ACKNOWLEDGMENTS

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REFERENCES

Berthe, M.G., Choukroune, P. and Jegouzo, P.
1979: Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican shear zone. Journal of Structural Geology, Volume 1, pages 31-42.

Blackwood, R.F.
1978: Northeastern Gander Zone. *In* Report of Activities for 1977. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-1, pages 72-79.

1982: Geology of the Gander Lake (2D/15) and Gander River area. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-4, 56 pages.

Colman-Sadd, S.P.
1980: Geology of south-central Newfoundland and evolution of the eastern margin of Iapetus. American Journal of Science, Volume 280, pages 991-1017.

Colman-Sadd, S.P. and Swinden, H.S.
1984: A tectonic window in central Newfoundland? Geological evidence that the Dunnage Zone is allochthonous. Canadian Journal of Earth Sciences, Volume 21, pages 1349-1367.

Currie, K.L. and Pajari, G.E.
1977: Igneous and metamorphic rocks between Rocky Bay and Ragged Harbour, northeastern Newfoundland. *In* Report of Activities, Part A, Geological Survey of Canada, Paper 77-1A.

Currie, K.L., Pajari, G.E. and Pickerill, R.K.
1979: Tectono-stratigraphic problems in the Carmanville area, northeastern Newfoundland. *In* Current Research, Part A. Geological Survey of Canada, Paper 79-1A, pages 71-76.

1980a: Comments on the boundaries of the Davidsville Group, N.E. Newfoundland. *In* Current Research, Part A. Geological Survey of Canada, Paper 80-1A, pages 115-118.

1980b: Geological map of the Carmanville map area (2E/8), Newfoundland. Geological Survey of Canada, Open File No. 721.

Hanmer, S.
1981: Tectonic significance of the northeastern Gander Zone, Newfoundland: an Acadian ductile shear zone. Canadian Journal of Earth Sciences, Volume 18, pages 120-135.

Jenness, S.E.
1958: Geology of the Gander River Ultrabasic Belt, Newfoundland. Geological Survey of Newfoundland, Report 11, 58 pages.

Kennedy, M.J. and McGonigal, M.H.
1972: The Gander Lake and Davidsville groups of northeastern Newfoundland: new data and geotectonic implications. Canadian Journal of Earth Sciences, Volume 9, pages 452-459.

Kilfoil, G.
This volume: Breathing new life into old data: colour images from the corrected, regional aeromagnetic dataset for insular Newfoundland.

Leger, A. and Williams, P.F.
1986: Transcurrent faulting history of southern New Brunswick. *In* Current Research, Part B. Geological Survey of Canada, Paper 86-1B, pages 111-120.

Miller, H.G.
1988: Geophysical interpretation of the geology of the northeast Gander Terrane, Newfoundland. Canadian Journal of Earth Sciences, Volume 25, pages 1161-1174.

1990: A synthesis of the geophysical characteristics of terranes in eastern Canada. Tectonophysics, Volume 177, pages 171-191.

O'Neill, P.
This volume: Geology of the southeastern part of the Gander Lake map area (NTS 2D/15) and the southwestern part of the Gambo map area (NTS 2D/16).

O'Neill, P. and Blackwood, R.F.
1989: A proposal for revised stratigraphic nomenclature of the Gander and Davidsville groups and the Gander River Ultrabasic Belt, of northeastern Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 127-130.

O'Neill, P. and Knight, I.
1988: Geology of the east half of the Weir's Pond (2E/1) map area and its regional significance. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 165-176.

O'Neill, P. and Lux, D.
1989: Tectonothermal history and ^{40}Ar/^{39}Ar geochronology of northeastern Gander Zone, Weir's Pond area (2E/1). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 131-139.

Pajari, G.E. and Currie, K.L.
1978: The Gander Lake and Davidsville groups of northeastern Newfoundland: a re-examination. Canadian Journal of Earth Sciences, Volume 15, pages 708-714.

Pajari, G.E., Pickerill, R.K. and Currie, K.L.
1979: The nature, origin and significance of the Carmanville ophiolitic mélange, northeastern Newfoundland. Canadian Journal of Earth Sciences, Volume 16, pages 1439-1452.

Piasecki, M.A.J.
1988: A major ductile shear zone in the Bay d'Espoir area, Gander Terrane, southeastern Newfoundland. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 135-144.

Piasecki, M.A.J., Williams, H. and Colman-Sadd, S.P.
1990: Tectonic relations along the Maelpaeg, Burgeo and Burlington Lithoprobe transects in Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 327-339.

Pickerill, R.K., Pajari, G.E. and Currie, K.L.
1978: Carmanville map area (2E/8): The northeastern termination of the Appalachains. *In* Report of Activities, Part A. Geological Survey of Canada, Paper 78-1A, pages 209-216.

1981: Resedimented volcaniclastics in the Carmanville area, northeastern Newfoundland—depositional remnants of Early Palaeozoic oceanic islands. Canadian Journal of Earth Sciences, Volume 18, pages 55-70.

Uzuakpunwa, A.B.
1973: Structural studies of the Gander and Davidsville groups in the Carmanville—Ladle Cove areas, Newfoundland. MSc Thesis, Memorial University of Newfoundland, St John's, 140 pages.

Williams, H., Colman-Sadd, S.P. and Swinden, H.S.
1988: Tectonic-stratigraphic divisions of central Newfoundland. *In* Current Research, Part B. Geological Survey of Canada, Paper 88-1B, pages 91-98.

Williams, H. and Piasecki, M.A.J.
1990: The Cold Spring Melange and a possible model for Dunnage-Gander zone interaction in central Newfoundland. Canadian Journal of Earth Sciences, Volume 27, pages 1126-1134.

Williams, P.F.
1983: Timing of deformation and the mechanism of cleavage development in a Newfoundland melange. Maritime Sediments and Atlantic Geology, Volume 19, pages 31-48.

Williams, P.F. and Hy, C.
1990: Origin and deformational and metamorphic history of gold-bearing quartz veins on the Eastern Shore of Nova Scotia. *In* Mineral Deposit Studies in Nova Scotia, Volume 1. *Edited by* A.L. Sangster. Geological Survey of Canada, Paper 90-8, pages 169-194.

Williams, P.F., Elliot, C.G. and Lafrance, B.
1988: Structural geology and Melanges of eastern Notre Dame Bay, Newfoundland. Geological Association of Canada—Mineralogical Association of Canada—Canadian Society of Petroleum Geologists, Field Trip Guidebook, 60 pages.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 109-126

THE GEOLOGY AND STRUCTURE OF THE GANDER–AVALON BOUNDARY ZONE IN NORTHEASTERN NEWFOUNDLAND

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ABSTRACT

In the western Bonavista Bay region, the steeply dipping Dover Fault separates a highly deformed sequence of volcanic rocks (Avalon Zone) from adjacent gneisses and granites (Gander Zone).

The metasedimentary rocks of the northeast Gander Zone show a progressive increase in structural complexity and volume of intruded granites toward the Dover Fault. A regional belt of sillimanite-grade gneisses (Hare Bay Gneiss) occurs adjacent to the fault. Within these gneisses, it is apparent that deformation, mobilization and granite emplacement processes are closely associated in both space and time. A regional phase of sinistral transpression occurred at medium to high metamorphic grades and was then overprinted by ductile deformation that occurred at a low metamorphic grade, producing the dextral Dover Fault and sinistral Cape Freels shear zone. Both these structures form broad zones of retrograde mylonites and phyllonites at least 1 km wide. Later brittle dextral faulting is concentrated within these shear zones and has caused extensive disruption of the earlier structures.

The volcanic rocks of the Avalon Zone adjacent to the Dover Fault, previously assigned to the Love Cove Group, are herein viewed to structurally and stratigraphically overlie late Precambrian–Early Cambrian clastic redbeds that are included here in the Musgravetown Group. This relationship would preclude correlation of this volcanic succession with older volcanic rocks of the Love Cove Group, the type area of which lies in a separate belt farther to the southeast. Within the study area, deformation of Avalon Zone rocks occurred at greenschist facies and increases in intensity and complexity toward the Dover Fault. A regional phase of sinistral transpression is overprinted by later ductile and brittle dextral movements in a zone up to 600 m wide adjacent to the Dover Fault.

It is suggested that the early sinistral transpressive events recognized in both the Gander and Avalon zones may be correlated and that they result from the initial juxtaposition of the two terranes during large-scale left lateral movements, which may have occurred during the Silurian. It appears that the Avalon Zone rocks within the study area have not undergone widespread Precambrian (Avalonian) orogenesis. Dextral brittle faulting in the western Bonavista Bay region could be an Acadian (Devonian) event, but, based on existing evidence from the study area, an Alleghenian age of movement cannot be discounted.

INTRODUCTION AND AIMS

Most recent tectonic models for Newfoundland suggest that the Gander–Avalon boundary represents a major tectonic discontinuity, along which large lateral displacements may have occurred, especially during Paleozoic orogenesis (e.g., Blackwood and Kennedy, 1975; Williams, 1979, 1984; Hanmer, 1981; Currie and Piasecki, 1989). Thus, it is generally regarded as an important example of an ancient terrane boundary within the Appalachian orogen.

This report summarizes the findings made in the first field season of a larger multidisciplinary project, which aims to study four problems relevant to the terrane boundary model:

1) the age and kinematic history of the Dover–Hermitage Bay fault system;
2) the age, geometric and kinematic history of orogenesis in the Gander Zone;
3) the nature and controls of magmatic emplacement mechanisms within the Gander Zone; and
4) the distribution and nature of late Precambrian (Avalonian) orogenesis in western Avalon Zone and its possible control on the formation of later Paleozoic structures.

Field studies in 1990 involved detailed mapping of several well-exposed coastal sections located mostly along the northwest shore of Bonavista Bay, northeast Newfoundland (Figure 1). Samples of igneous intrusions and country rocks were collected for isotopic dating in an attempt to erect a chronological framework for structural, metamorphic and igneous sequences that will be established during the project.

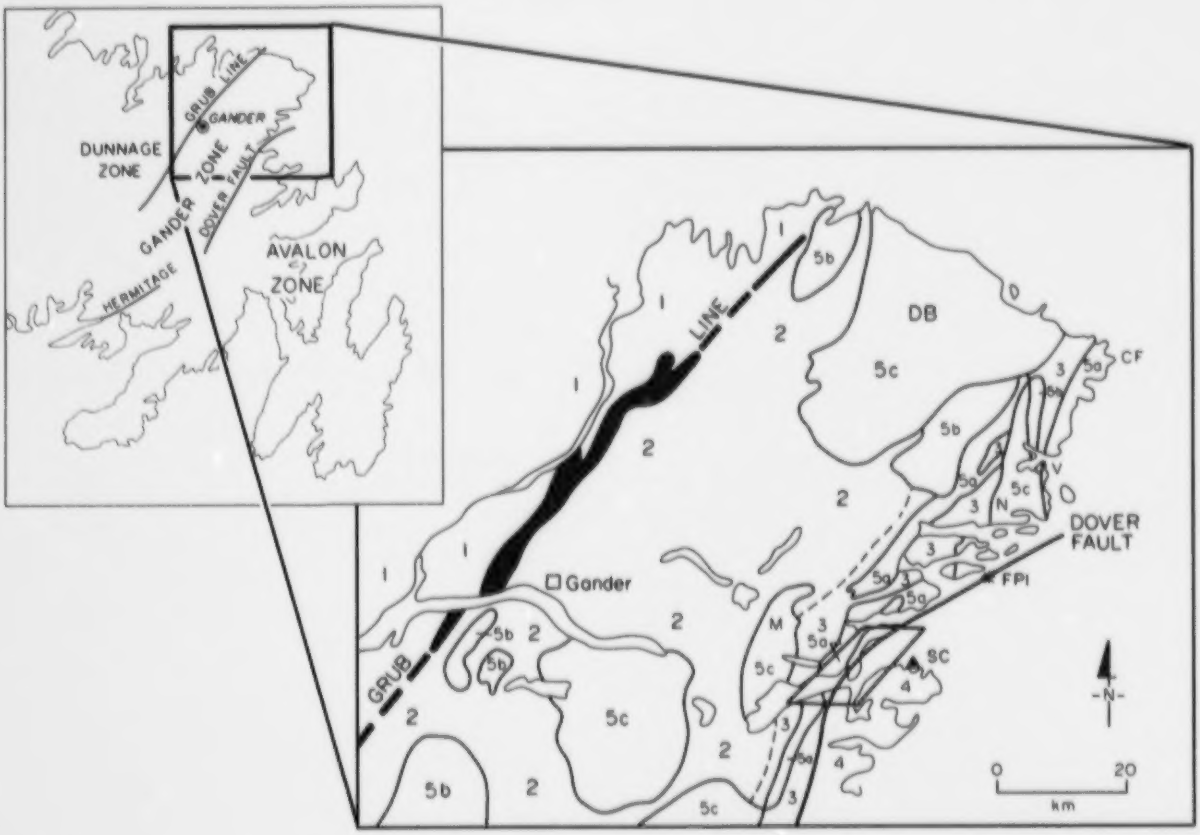


Figure 1. *Inset is map of eastern Newfoundland, showing Avalon, Gander and Dunnage zones and location of larger figure, which is a simplified geological map of northeast Newfoundland. [Box along bend in Dover Fault shows location of Figure 2.] Dunnage Zone (1), Gander Group (2), Hare Bay Gneiss (3), Avalon Zone (4), foliated megacrystic granites (5a), foliated two-mica granites (5b), unfoliated megacrystic granites (5c). CF=Cape Freels, V=Valleyfield, M=Middle Brook Granite, N=Newport Granite, DB=Deadmans Bay Granite, SC=Shatter Cove, FPI=Frying Pan Island.*

REGIONAL SETTING

The Avalon and Gander zones form the eastern elements of the Appalachian orogenic belt in Newfoundland (Williams *et al.*, 1974; Williams, 1979). In the Bonavista Bay region, they are separated by a prominent zone of faulting known as the Dover Fault (Figure 1; Younce, 1970; Blackwood and Kennedy, 1975).

The rocks of the Gander Zone lying to the northwest of the Dover Fault belong to the Gander Lake Subzone (Williams *et al.*, 1988), which comprises a thick sequence of strongly deformed metasedimentary rocks (Gander Group) and gneisses (Hare Bay Gneiss) intruded by granites (e.g., Jenness, 1963; Williams, 1968; Kennedy and McGonigal, 1972; Jayasinghe, 1978). Some studies (e.g., Blackwood and Kennedy, 1975; Blackwood, 1976, 1977) led to the belief that the gneisses were the basement to the Gander Group, but others led to the conclusion that the rocks are part of a continuous, conformable succession that has undergone increasing intensities of metamorphism eastward (Jenness, 1963; Blackwood, 1978; Hanmer, 1981). With the exception of part of the Indian Bay Big Pond formation (O'Neill and Blackwood, 1989), which contains Arenig–Llanvirn fauna of mixed North American/Balto-Scandian aspect (Wonderley and Neumann, 1984), the Gander Group is unfossiliferous. This formation is thought to be intercalated with the upper parts of the Gander Group, but no fossils are found *in situ* and contact relationships are mostly inferred (e.g., see O'Neill and Knight, 1988). Thus, the evidence for a lower Palaeozoic age for the Gander Group remains open to question. Deformation within the Gander Lake Subzone involves complex folding and fabric formation, with several authors erecting polyphase structural sequences, which usually suggest increasing complexity eastward, associated with a higher metamorphic grade (e.g., Jenness, 1963; Blackwood, 1976, 1977, 1978). Granitic intrusions are abundant in the Gander Lake Subzone, particularly within the higher grade regions to the east (Figure 1). It has long been suggested that there are distinct intrusive sequences and that many of the earlier granites are deformed and contain fabrics also recognized within the country rocks (Jayasinghe and Berger, 1976; Blackwood, 1976, 1978; Jayasinghe, 1978). Some authors, notably Hanmer (1981), have favoured a tectonic model, in which granite emplacement and progressive deformation of the country rocks occur synchronously, and in which much of the Gander Lake Subzone is a major, crustal-scale shear zone. Deformation and plutonism are usually assigned to the loosely defined Siluro-Devonian Acadian Orogeny, as Rb–Sr whole-rock data from the granites give ages in the range ca. 440 to 300 Ma (Blenkinsop *et al.*, 1976; Bell *et al.*, 1977, 1979). However, similarities between this region and the Hermitage Flexure area of southern Newfoundland, where widespread Silurian orogenesis within the region adjacent to the northwest margin of the Avalon Zone has been documented (e.g., Dunning *et al.*, 1990; O'Brien *et al.*, 1991), suggest that events recorded in both areas may be in part coeval.

The rocks of the Avalon Zone, which lie to the southeast of the Dover Fault are a sequence of low-grade, weakly to moderately deformed sedimentary and volcanic rocks of late Precambrian age, overlain by shallow-marine Cambro-Ordovician strata (see O'Brien *et al.*, 1990, for review). The oldest known rocks in the Avalon Zone belong to the Burin Group, a sequence of mafic volcanic and volcaniclastic rocks intruded by gabbro dated at 763 ± 2 Ma; all are thought to be of oceanic affinity (Strong *et al.*, 1978; Krogh *et al.*, 1988). The Burin Group is fault-bounded and there is no obvious link between these rocks and subsequent Precambrian events within the Avalon Zone. Between about 635 and 560 Ma, a complex history of bimodal volcanism, comagmatic plutonism and sedimentation within fault-bounded basins characterizes the entire Avalon Zone in Newfoundland (O'Brien *et al.*, 1983; Krogh *et al.*, 1988; O'Brien *et al.*, 1990). In general, marine flyschoid sedimentary rocks give way to predominantly deltaic and fluviatile deposits (King, 1980) and in many regions, a widespread angular unconformity is recognized separating older marine clastic rocks from overlying redbeds (Hayes, 1948; Anderson *et al.*, 1975). A second major unconformity separates the Cambro-Ordovician platformal sedimentary rocks from underlying late Precambrian strata (e.g., McCartney, 1967). It is generally agreed that the Precambrian rocks were affected by significant deformation and low-grade metamorphism prior to the Cambrian; this event is known as the Avalonian Orogeny (Lilly, 1966; Hughes, 1970). The precise timing and distribution of events remains uncertain, although recent work (e.g., O'Brien, 1987) suggests that deformation may be localized along certain prominent fault systems. The unconformable Lower Cambrian to Arenig platformal sedimentary rocks are unaffected by Avalonian events; they contain a characteristic Acado-Baltic trilobite fauna (Hutchinson, 1962). No post-Arenig to pre-Devonian rocks are exposed onshore, but offshore seismic reflection profiles (Durling *et al.*, 1987) reveal a thick, folded sequence of Ordovician and Silurian shales unconformably overlain by Devonian redbeds; the folding is thought to be the product of Acadian orogenesis. Onshore, the Acadian event produced widespread low-grade metamorphism, folding, fabrics and faulting, especially in the western Avalon Zone (Williams *et al.*, 1974; Dallmeyer *et al.*, 1981). Existing time constraints are poor, with ^{40}Ar–^{39}Ar plateau ages between 400 and 353 Ma for whole-rock phyllites, and between 356 and 352 Ma hornblende ages for posttectonic granites, suggesting a Devonian age for orogenesis (Dallmeyer *et al.*, 1981, 1983). There is little geological evidence for significant post-Acadian orogenic activity within the Avalon Zone.

The Dover Fault separates the upper amphibolite-facies gneisses of the Gander Zone from the greenschist-facies volcanic rocks of the Avalon Zone (Figure 1). It is this contrast in metamorphic grade, together with a lack of obviously correlatable events between the two zones, which makes the Dover Fault the most prominent geological boundary within the Newfoundland Appalachians. It is steeply dipping and is usually described as a mylonite zone between 300 to 500 m across (Blackwood and Kennedy, 1975; Blackwood, 1977, 1978). Deep-seismic data (Keen *et al.*, 1986) suggest that the fault cuts much, if not all, of the crust and that it separates deep crustal blocks of markedly different character. Recent structural studies (Hanmer, 1981; Caron and Williams, 1988a, b) suggest that the Dover Fault has accommodated several phases of substantial strike-slip displacement which, together with the other geological evidence described above, implies that the fault represents an Appalachian terrane boundary. Displacements are usually attributed to Acadian deformation, based on ^{40}Ar–^{39}Ar dating of fault-zone phyllites (400 to 353 Ma; Dallmeyer *et al.*, 1981) and the ca. 356 Ma age of the posttectonic Ackley Granite, which crosscuts the Dover Fault to the south (Dallmeyer *et al.*, 1983; Tuach, 1987). Mylonitic fabrics associated with the Dover Fault are thought to be continuous with later stage Acadian fabrics in both the Avalon and Gander zones (e.g., Blackwood, 1977, 1978).

NORTHEAST GANDER ZONE

INTRODUCTION

The present study has concentrated principally on the easternmost, highest grade metamorphic unit of the Gander Lake Subzone, the Hare Bay Gneiss (Figure 1). However, reconnaissance studies were also carried out on the adjacent Gander Group, including rocks previously assigned to the Square Pond Gneiss of Blackwood (1977). The work reported here supports the hypothesis that the sub-divisions belong to a single continuous sedimentary sequence, which according to Blackwood (1977, 1978), were subjected to increasingly high metamorphic grade eastward. The Hare Bay Gneiss is intimately associated with a number of granitic intrusions on a cm to km scale. Many of these granites are deformed together with the country rocks to differing degrees, and it would appear that this has led to an important oversight by many previous workers. In most areas, significant amounts (<50 percent) of the country rocks are orthogneisses, which appear to represent slightly earlier, petrographically identical equivalents of the granitic bodies mapped previously. They are 'gneisses' simply because they exhibit strong, solid-state deformation fabrics, often with very well-developed S-C fabrics, and, in some cases, folds. This reinforces the observation that there is a marked eastward increase in the volume of intruded granite, in addition to the rise in metamorphic grade and structural complexity.

Coastal sections were studied in Freshwater Bay, Hare Bay, Shoal Bay, Lockers Bay, Indian Bay, Valleyfield and Cape Freels–Windmill Bight (Figure 1).

HARE BAY GNEISS

This diverse assemblage was first defined by Blackwood (1976, 1977) as a zone of high-grade migmatites, tonalitic orthogneisses and rafts of paragneiss. The present study suggests that the complex can be broadly sub-divided into three components in order of relative age: metasedimentary rocks and amphibolites, mobilized gneisses, and orthogneisses. It is often impossible to map out individual components, first, because they are so intimately intermingled and second, because boundaries are often gradational over distances of up to several tens of metres. Furthermore, the orthogneisses essentially grade into deformed granites, forming early sheeted vein complexes (see below).

Metasedimentary Rocks and Amphibolites

These occur as enclaves and rafts on mm to km scale, and are especially common around Hare Bay, Shoal Bay, western Lockers Bay, central Indian Bay, Valleyfield and Windmill Bight. The metasedimentary rocks are migmatized semipelite, psammite and pelite interbanded on a scale of millimetres to centimetres. Sedimentary way-up criteria were not observed in these rocks. Rare bands of marble and skarn rocks form subordinate units normally less than 1 m thick. Uniform dark greenish-black amphibolites form units up to several hundreds of metres thick, but are only abundant in the area between Lockers Bay Granite and the Dover Fault (Hanmer, 1981). Contacts of amphibolite with metasedimentary rocks are in most places sharp and concordant, but the preservation of a massive igneous texture in regions of low tectonic strain (e.g., Shoal Bay) suggests that the amphibolites may represent mafic intrusive sheets. They carry all the deformational fabrics recognized within the metasedimentary rocks, which suggests that they were intruded at a very early stage in the tectonic history. Lithologically, the metasedimentary rocks and amphibolites are identical to the rocks of the Gander Group (including the Square Pond Gneiss of Blackwood, 1978); the boundary between Blackwood's Hare Bay and Square Pond gneisses was placed where migmatization becomes an ubiquitous feature (Blackwood, 1977, 1978).

Mobilized Gneisses

These are clearly derived from a greater degree of melting of the same metasedimentary country rocks, which occur as numerous small enclaves 'floating' within the granitic to tonalitic leucosome. They range from a relatively coherent, soaked migmatite (Freshwater Bay, Shoal Bay, Lockers Bay East; Plate 1), through to a thoroughly mobilized xenolithic granite (*sensu lato*, Indian Bay; Plate 2).

Orthogneisses

These comprise a series of tonalitic to granitic units, which do not usually include large numbers of country-rock enclaves, and which are not obviously derived from melting or mobilization of the immediately surrounding metasedimentary rocks. The earliest bodies are discrete granitic gneiss sheets found in the Indian Bay and Windmill Bight regions. They are deformed by the main phase of folding observed in the country rocks and only rarely preserve good igneous textures in zones of low strain. Later orthogneisses carry a strong solid-state tectonic fabric, which may include S-C textures, but early folds are mostly absent. They increasingly preserve good igneous textures and pass gradationally into the granitic intrusive suite described below. However, the possibility that at least some of the orthogneisses represent a much earlier phase of igneous intrusion cannot be ruled out based on preserved field relationships.

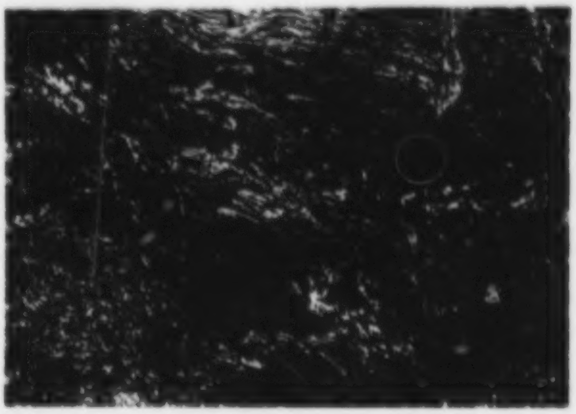


Plate 1. *Semi-pelitic migmatites of the Hare Bay Gneiss, western Hare Bay. Open to close upright Early Ductile folds refold earlier flat-lying isoclines; note that the segregation fabric is deformed by both sets of folds.*

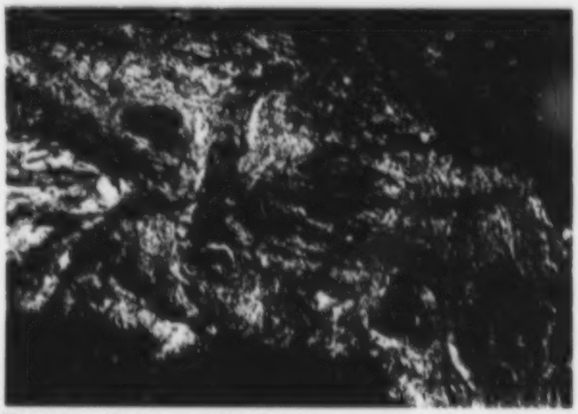


Plate 2. *Highly mobilized gneiss grading into a deformed xenolithic granite, Hare Bay Gneiss, Indian Bay. Note the contorted and irregular form of the cm-scale Early Ductile folds, which implies a lack of mechanical coherence.*

INTRUSIVE ROCKS

Igneous intrusions form a major component of the northeast Gander Zone and are increasingly abundant toward

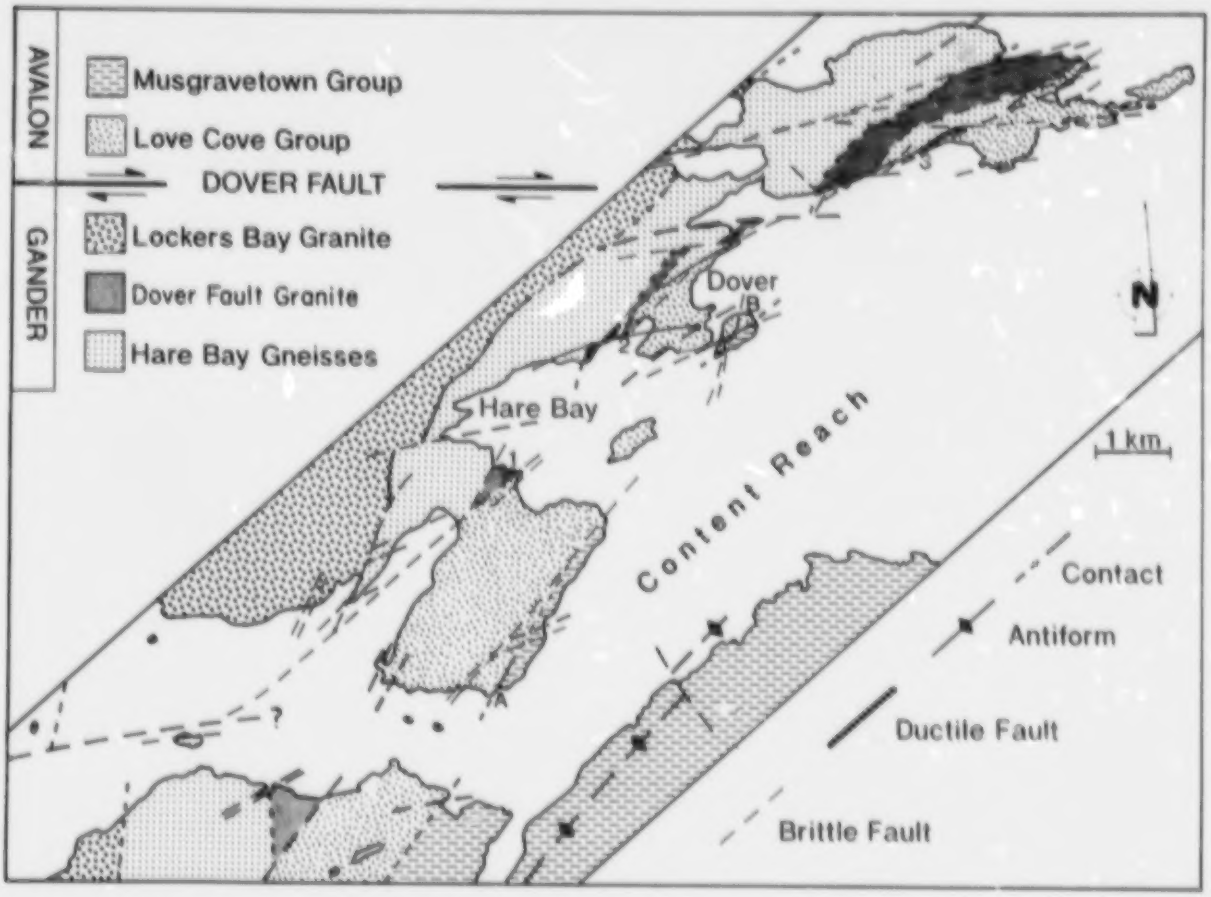


Figure 2. *Geological map of the Hare Bay–Dover region, Bonavista Bay. A and B are locations of exposed conformable contacts between the Musgravetown Group and younger volcanic rocks; other contacts are faulted. 1, 2 and 3 refer to location sites. See text for details.*

the Dover Fault (Figure 1). The majority are broadly granitic in composition, and can be sub-divided into five main groups: aplogranite veins, early sheeted complexes, foliated megacrystic biotite granites, two-mica garnetiferous granites, and unfoliated megacrystic biotite granites (Figure 1; Blackwood, 1978).

The aplogranites are a minor intrusive phase. They are fine-grained, pinkish-grey granites, which in many areas form irregular and anastomosing networks within parts of the Hare Bay Gneiss. They commonly contain biotite and are crosscut by all other intrusive phases.

The sheeted complexes are entirely restricted to the Hare Bay Gneiss and are in many areas spatially associated with, and crosscut by, the foliated megacrystic granites, notably the Dover Fault and Lockers Bay granites (Figure 2) and the Cape Freels granite. They comprise a diverse series of foliated dioritic to granitic sheets intruded into the Hare Bay Gneiss sub-parallel to the regional foliation. In general, the earliest sheets are the most mafic, whereas the latest are granites of very similar composition to the nearby megacrystic intrusions. The intrusions are all strongly foliated (±S-C fabrics) and, where they contain numerous enclaves of metasedimentary rocks (e.g., East Lockers Bay), both are deformed by folds and fabrics identical to the structures associated with the main phase of early deformation seen elsewhere in the Hare Bay Gneiss. As this is apparently the same phase that is associated with high-grade metamorphism and mobilization in the gneisses, it suggests that intrusion of the sheeted complexes occurred at the same time or soon after these events. This proposal is consistent with the apparent gradation between early granite sheets and 'later' orthogneisses.

The foliated megacrystic biotite granites are mostly coarse-grained, linear bodies, largely restricted to the extreme southeast parts of the Hare Bay Gneiss. One discontinuous sheeted unit, the Dover Fault Granite, lies close to and sub-parallel with the Dover Fault (Figure 2; Blackwood, 1977). All these granites carry weak to strong, steeply dipping, northeast-striking foliations, of which a significant component is a 'pre-full crystallization' (PFC) fabric (*sensu* Hutton, 1988). The PFC fabrics comprise a strong alignment of K-feldspar phenocrysts, together with highly flattened and 'smeared out' dioritic enclaves, which are locally abundant within most of the granites. Narrow sheets of deformed biotite–muscovite–garnet–tourmaline-bearing leucogranite and pegmatite (mostly less than 2 m thick) are found within many of the megacrystic granites, notably the Cape Freels and Lockers Bay bodies. These sheets lie at low angles or sub-parallel to the foliation in the granite host, and are uncommon in the surrounding country rocks.

The medium- to coarse-grained, two-mica garnetiferous granites range from early foliated plutons that are elongate in the regional foliation, to irregular fine-grained bodies that lack any foliation (e.g., Jayasinghe and Berger, 1976; Blackwood, 1978). They occur throughout the Gander Zone (Figure 1; Blackwood, 1978) and consistently crosscut foliated megacrystic granites.

The final group, the unfoliated megacrystic biotite granites, form some of the largest and latest intrusive plutons found within the Gander Zone. Certain bodies have locally foliated and deformed marginal phases (Middle Brook, Deadmans Bay), whereas others crosscut all structures and other intrusions. Because of its crosscutting relationships with adjacent rocks and its largely undeformed nature, the Newport Granite has historically been viewed as the youngest pluton in the region (cf. Jayasinghe, 1978).

Two sets of minor intrusions occur sporadically in that part of the Gander Zone that was studied. Rare, foliated micro-diorites form steeply dipping sheets that mostly lie at low angles or sub-parallel to the regional foliation. Most are less than 1 m thick, and although they apparently crosscut local migmatitic fabrics in the Hare Bay Gneiss (e.g., Freshwater Bay), others are apparently included as enclaves elsewhere (e.g., Indian Bay). Similar in habit to syn-plutonic dykes, they apparently represent a localized phase of intermediate composition, temporally associated with the mobilization of the gneisses and intrusion of the granites.

Finally, unfoliated diabase dykes, up to 3 m thick, occur locally within the Hare Bay Gneiss and almost all the large granitic bodies. They are crosscut by the Newport Granite (Jayasinghe, 1978). Most dykes trend north-northeast and are sub-vertical in orientation.

STRUCTURAL GEOLOGY

Recent structural studies within the Gander Group (e.g., O'Neill, 1987; O'Neill and Knight, 1988; O'Neill and Lux, 1989; O'Neill and Blackwood, 1989) demonstrate a general increase in deformational complexity with rising metamorphic grade. An early, bedding-parallel fabric (S1) is folded around numerous small-scale isoclinal F2 folds, which are associated with a strong axial-planar S2 cleavage and northeast-trending subhorizontal mineral lineation. These structures are in turn refolded by upright, northeast-trending F3 folds, which become dominant within the Gander Group's higher grade, more highly deformed parts. The peak of low-pressure–high-temperature regional metamorphism is apparently synchronous with, or slightly later than this F3 folding (O'Neill and Lux, 1989). Data collected on reconnaissance traversing during the present study indicate that the dominant phase of folding and associated fabrics recognized within the Hare Bay Gneiss–here termed the Early Ductile structures–are broadly equivalent to the F3 folds farther west.

Early Ductile Structures

The dominant structures within the Hare Bay Gneiss are a series of mm- to km-scale folds whose steeply dipping to vertical axial planes trend northeast. Deformation associated with the folding is responsible for the regional tectonic fabric and is intense throughout much of the Hare Bay Gneiss. A well-developed sub-horizontal to shallowly plunging, northeast-trending mineral lineation is widespread, but locally has rotated into steep reclined orientations, often over distances of only a few centimetres (e.g., Windmill Bight, Figure 3a, b). Minor folds are typically highly curvilinear about the local lineation, and may display up to 180° of hinge curvature over a few millimetres (Figure 3a, b). Thus, the entire belt is characterized by variably plunging lineations, minor folds and complex changes in the senses of fold vergence (Figure 3a). In detail, most minor folds of this generation fold the mineral lineation about which they are curvilinear, a feature typical of progressive deformation in ductile shear zones (e.g., Holdsworth, 1990).

Small-scale isoclinal folds whose axes lie parallel to the mineral lineation are refolded by the regionally dominant fold set in many exposures (e.g., Plate 1). However, these structures are only preserved in metasedimentary gneisses or amphibolites, not in orthogneisses or granites. These early isoclines deform a still earlier bedding parallel fabric, suggesting that the regionally dominant fold set is pre-dated by at least two phases of deformation (cf. F3 folds in the Gander Group).

The Early Ductile deformation is clearly associated with high temperatures, as indicated by the widespread preservation of syn- to post-kinematic sillimanite needles (e.g., Indian Bay) suggesting upper amphibolite-facies conditions. Deformational fabrics are strongly recrystallized within the coarse-grained gneisses, whereas increased strain intensities in some localities have clearly induced the process of mobilization (e.g., Lockers Bay, Indian Bay). In other areas, notably western Freshwater Bay and Indian Bay, the same deformational phase has produced very different styles of folding within adjacent large-scale units of mobilized gneiss and less migmatized metasedimentary rock. In the latter units, the folds are similar to those shown in Figure 3a, whereas geometrically unpredictable, highly irregular and contorted structures (e.g., Plate 2) characterize the mobilized units. These observations suggest that the latter constitute a much less coherent rheology at the time of deformation. However, it would appear that the relative timing of mobilization and folding is variable, because some areas of such rocks show perfectly coherent patterns of folding (e.g., eastern Freshwater Bay).

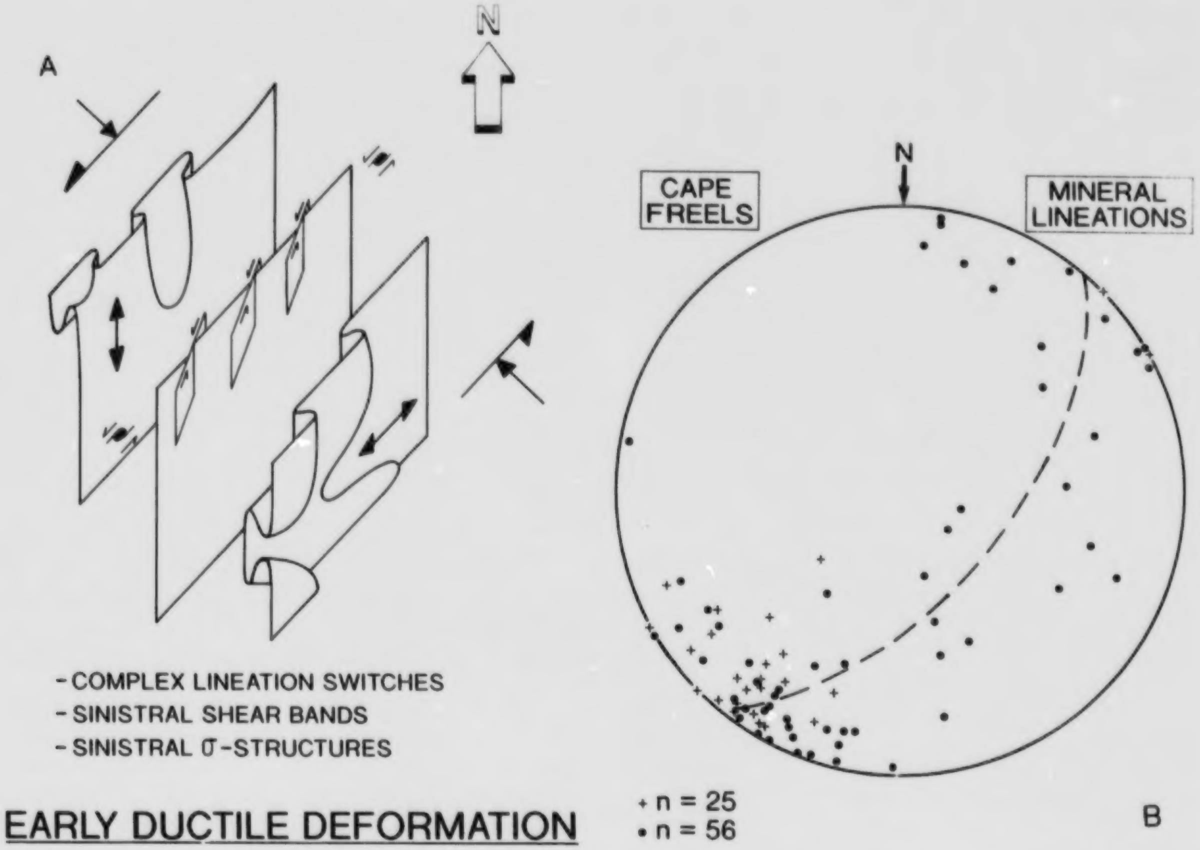


Figure 3. *a) 3-dimensional diagram summarizing the geometry of Early Ductile deformation structures in the northeast Gander Zone, Bonavista Bay. The two outer panels show the two extremes in orientation of the lineation and associated sheath folds, whereas the central panel shows the sinistral shear bands and σ-structures that occur throughout the region. b) Stereoplot of lineations from the Cape Freels–Windmill Bight area (for location see Figure 1). Solid dots are lineations from the Hare Bay Gneiss; crosses are from the Cape Freels Granite. Dashed line gives the mean regional foliation. Note the predominance of shallowly plunging northeast-southwest lineations, with a smaller group of steeply plunging lineations (cf. Figure 3a).*

Shear-sense criteria are abundant within the Hare Bay Gneiss, especially the more homogeneous mobilized gneisses and orthogneisses. They include: cm- to mm-spaced shear bands (Plate 3), asymmetric wrapping of metasediment–amphibolite enclaves in mobilized gneisses (Plate 4), σ-porphyroclasts and shearing of passive markers across strain gradients (e.g., dykes). All these features give sinistral senses of shear throughout the region. Note that in areas where minor folds are curvilinear about a shallowly plunging lineation, they predominantly display sinistral senses of vergence as they pass through the vertical (Figure 3a). Shear criteria in areas where the lineation has steep plunges give both northwest- and southeast-side-up senses of movement. Many shear bands carry thin streaks of leucosome (Plate 3), which, together with the evidence for sinistral shear during mobilized flow (Plate 4) suggest, once again, a close association between mobilization and deformation. Viewed as a whole (Figure 3a), the Early Ductile structural configuration is most readily interpreted as arising from a regional sinistral transpression which occurred, presumably, at upper-amphibolite facies.

Late Ductile Structures

These ductile structures are mostly restricted to localized shear zones and are immediately distinguishable from the earlier structures as they are usually associated with much lower grade, phyllonitic fabrics. Two principal shear zones are recognized, both of which are much disrupted by later brittle faulting; one is dextral and follows the trace of the Dover Fault, whereas the other is sinistral and is associated with the western contact of the Cape Freels Granite (Figure 4a). In addition, a number of small-scale, generally east-trending dextral phyllonitic shear zones cut the gneisses in several locations (Figure 4a).

The Dover Fault dextral shear zone affects rocks up to 1 km from the Gander–Avalon zone boundary. With

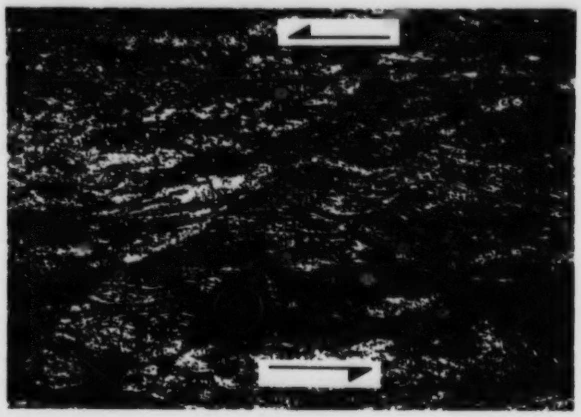


Plate 3. *Centimeter-spaced sinistral shear bands in tonalitic, mobilized Hare Bay Gneiss, Freshwater Bay. Note the thin streaks of leucosome that have formed along the shear planes.*

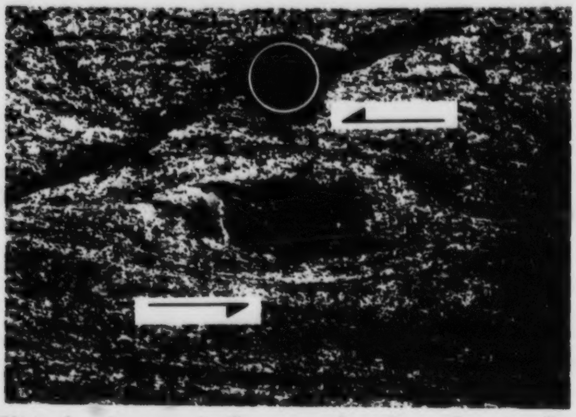


Plate 4. *Asymmetrically wrapped enclave of semi-pelite within deformed mobilized gneiss, Hare Bay Gneiss, Lockers Bay. Sinistral shear apparently occurred at, or near to the time of mobilization.*

proximity to the shear zone, the gneisses become increasingly epidote- and chlorite-rich and are green; this is due to retrograde metamorphism. Grain-size reduction fabrics are preserved in areas of higher strain. A zone (up to 300 m width) of dark green, chlorite–sericite phyllonite derived from the gneisses is present at the Gander–Avalon contact (Figure 4b). These almost always contain highly sheared pink veins of Dover Fault Granite.

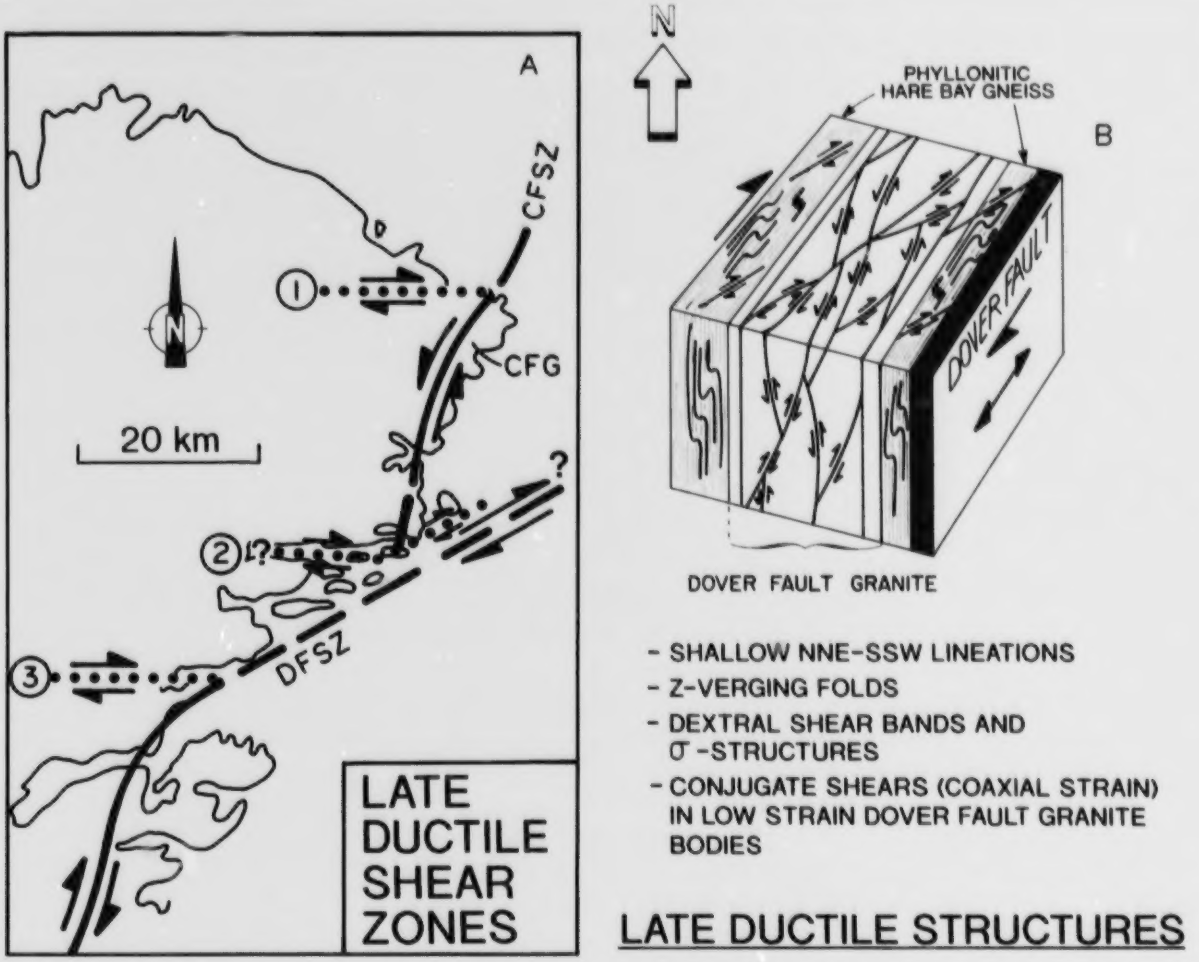
The low-grade shearing deforms the larger Dover Fault Granite sheets (Figure 2). The biggest of these form resistant augen of lower strain, crosscut by networks of steeply dipping, conjugate sinistral and dextral phyllonitic shear zones (Figure 4b); these reach widths of a few cm. In the margins of the granite, and in the adjacent phyllonitic gneisses, lineations have sub-horizontal or gently plunging northeast-southwest orientations. Shear-sense criteria (shear bands, σ-structures, asymmetric sheath folds) all give dextral senses of shear (Figure 4b). Similar structures give dextral shear senses within the east-trending, sub-vertical shear zones (up to 50 m wide), which cut the gneisses in Lockers Bay, Indian Bay and Windmill Bight (Figure 4a). Fabrics and folds developed during the earlier higher grade metamorphism are strongly reworked and refolded within these shear zones.

The north-northeast-trending shear zone associated with the western margin of the Cape Freels Granite (Figure 4a) forms a belt at least 500 m wide, of greenschist-facies mylonites affecting both granite and adjacent gneisses. It is much disrupted by later faulting, and lower grade mylonitic gneisses are only well exposed in the Valleyfield coastal section; they are absent at the faulted contact at Cape Freels. Shear bands, asymmetric sheath folds, and σ-structures give sinistral senses of shear in surfaces oriented parallel to the shallowly plunging mineral lineation. Earlier folds and fabrics are strongly refolded and reworked, and are well preserved in metre-scale sinistral shear augen exposed in the Valleyfield section, as noted by Hanmer (1981). He has also described the marginal shear zone in the Cape Freels granite, which displays a spectacular series of protomylonitic to ultramylonitic S-C deformation textures. Low-grade sinistral and subordinate dextral shear bands are preserved within the western part of the granite up to 1 km from the contact, and overprint an earlier PFC foliation within the pluton.

At the southernmost outcrops of the Cape Freels Granite around Fox Bay, where it is crosscut by the undeformed Newport Granite (Jayasinghe, 1978), narrow, steeply northwest-dipping dextral reverse shear zones are abundant. These structures are associated with refolding of the earlier PFC fabric and may be related to dextral transpressive movements along the offshore extension of the Dover Fault (Figure 4a).

Late Brittle Structures

Complex linked systems of steeply dipping faults are widespread in the region and are concentrated in the vicinity of the Dover Fault and Cape Freels Late Ductile shear zones. Many larger faults have markedly controlled the local present-day physiography (e.g., Figure 2). Individual faults are often marked by narrow (< 1 cm) veins of epidotic cataclasite, or broader zones (<50 m) of breccia (Figure 5). Shear fibres and slickensides, where present, usually have shallow plunges, suggesting that strike-slip movements are dominant. In the Hare Bay–Dover area, the pre-existing arrangements of lithological units and phyllonite zones are highly disrupted by faulting on a cm to km scale (Figures 2 and 5). Three predominant fault orientations and displacement senses (as deduced from offsets) are recognized: east–east-northeast dextral, northeast-dextral, and north–north-northeast sinistral. These fracture patterns appear to best correspond to R (or Y), P and R' shears (*sensu* Tchalenko, 1970) associated with movements along a northeast-trending dextral fault zone. In well-exposed sections (Figure 5), distinct domains of R, P and R' faults are recognized, constituting an array of rotating fault blocks that are typical of brittle strike-slip deformation zones (e.g., Nur *et al.*, 1989). Within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- SHALLOW NNE-SSW LINEATIONS
- Z-VERGING FOLDS
- DEXTRAL SHEAR BANDS AND σ-STRUCTURES
- CONJUGATE SHEARS (COAXIAL STRAIN) IN LOW STRAIN DOVER FAULT GRANITE BODIES
LATE DUCTILE STRUCTURES

Figure 4. *a) Late Ductile shear zones in the Bonavista Bay area. DFSZ=Dover Fault shear zone; CFG=Cape Freels Granite; CFSZ=Cape Freels shear zone. The dotted lines show the orientations of minor shear zones of the same age in a number of locations; 1–Windmill Bight, 2–Indian Bay and 3–Lockers Bay. b) 3-dimensional diagram summarizing the geometry of Late Ductile structures along the Dover Fault shear zone. Where larger bodies of Dover Fault Granite occur (see Figure 2), a central zone of less-deformed coaxial strain in the granite separates highly non-coaxial phyllonites derived mostly from retrogressed Hare Bay Gneiss. The latter preserve abundant shear criteria including shear bands, σ-structures and dextrally verging folds. The central coaxial strain unit is absent in areas lacking large Dover Fault Granite bodies.*

these zones, extremely complex second-order fault-block arrays are developed in order to accommodate compatibility problems and fault-block shape changes during displacements along first-order (i.e., mappable) fault systems. Kinematic interpretations of fault patterns at the scale of individual exposures should be treated with caution, as complex localized systems of second-order transpression and transtension are to be expected (Wilcox *et al.*, 1973).

Similar fault arrays are associated with the Cape Freels Late Ductile shear zone, suggesting that the earlier sinistral movements are overprinted by regional Late Brittle dextral displacements.

STRUCTURAL AGES OF GRANITIC INTRUSION

All granites examined during the present study of the northeast Gander Zone are crosscut by brittle faults. The Newport Granite, the apparently youngest pluton studied, is crosscut by a complex fault system exposed on Frying Pan Island (Figure 1), as recognized by Blackwood (1977). A detailed analysis of these structures demonstrates that they have formed in association with dextral displacements along a northeast-trending master fault, which may be the northeast extension of the Dover Fault.

The unfoliated megacrystic biotite granites studied (Newport, Middle Brook, Deadmans Bay), together with a

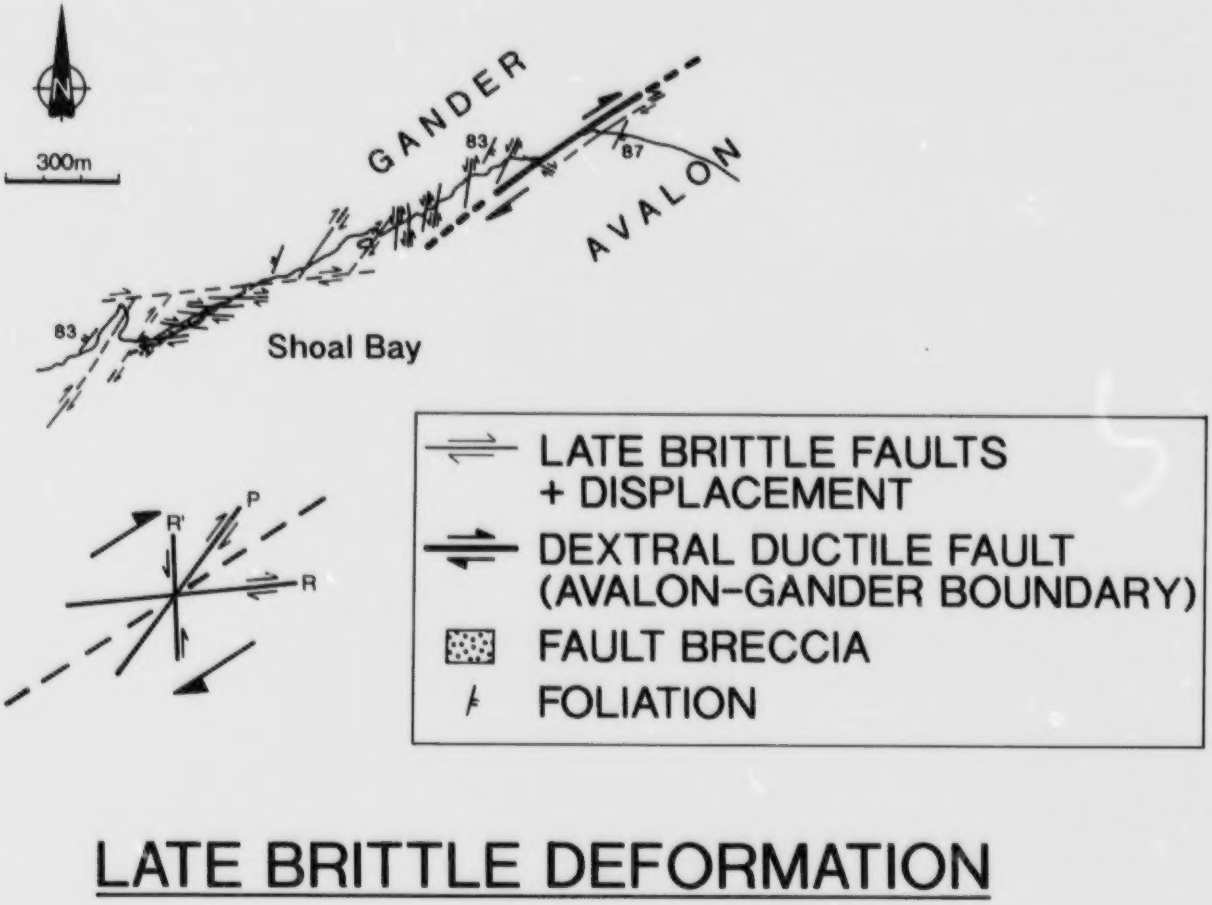

Figure 5. *Detailed map of the boundary of the Gander and Avalon zones (North Shoal Bay), showing late Brittle faulting patterns associated with dextral displacements along a presumed northeast-trending master fault. Note that the original Late Ductile dextral Dover Fault contact is preserved here (location 3 in Figure 2).*

number of small unfoliated two-mica granite bodies in the Indian Bay and Freshwater Bay areas, appear to postdate all ductile structures in the surrounding country rocks.

It is tentatively suggested that the majority of foliated granites within the northeast Gander Zone were intruded during deformation of the surrounding country rocks producing internal PFC and/or solid-state deformation fabrics (*sensu* Hutton, 1988). The earliest bodies (aplogranites, early members of sheeted granitic complexes, Freshwater Bay granite) contain strong solid-state S-C fabrics and folds that give sinistral shear-senses; it is proposed that they were intruded synchronously with the Early Ductile deformation. The Cape Freels granite carries an early PFC fabric, which is overprinted by low-grade solid-state fabrics, especially along its western margin. Fractured phenocrysts, flow folding and offsets along internal leucogranite sheets (Plate 5) all suggest sinistral shearing during emplacement of the granite, and this event is correlated with the later stages of the Early Ductile event. The Lockers Bay and Dover Fault granites

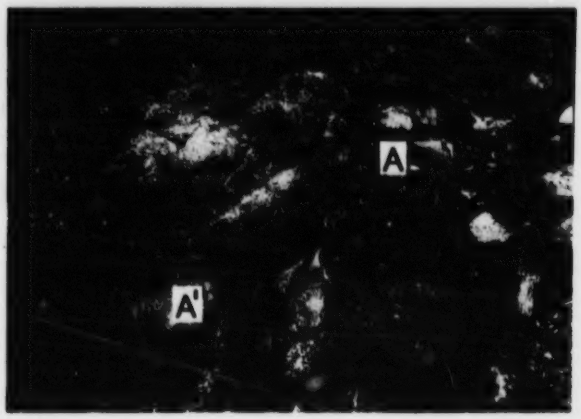

Plate 5. *Fine- to medium-grained leucogranite dykes of the Cape Freels Granite crosscutting the main granite, Cape Freels. Dyke A is offset in a sinistral sense to A' along a slightly later northeast-trending dyke.*

(Figure 2, Blackwood, 1977) are strongly deformed by greenschist-facies shearing associated with dextral transpressive Late Ductile movements along the Dover Fault shear zone (e.g., Figure 4b). Farther northwest, parts of the Lockers Bay, Freshwater Bay and sheeted granite complexes are deformed by narrow (<5 m) foliation-parallel phyllonitic shear zones displaying dextral and/or northwest-side-up senses of shear (S-C fabrics). A Late Ductile age of shearing seems likely based on textural similarity with the Dover Fault shear zone. The Dover Fault Granite does not appear to contain an earlier PFC fabric, based on field observations, and its intrusion is therefore proposed to have been post-Early Ductile, pre-Late Ductile deformation. In contrast, the Lockers Bay Granite carries a strong PFC S-fabric, which in several locations is folded by cm- to mm-scale folds with a consistent dextral sense of vergence. These folds are not associated with solid-state fabrics and they appear to represent early PFC structures. Many seem to have formed during magma flow around resistant enclaves of basic material (e.g., Freshwater Bay). Whereas these structures could be related to local flow within the magma, their consistent vergence over a wide area may indicate that the Lockers Bay Granite was emplaced during the initial stages of dextral Late Ductile movements.

NORTHWEST AVALON ZONE

INTRODUCTION

The rocks of the Avalonian succession in southwest Bonavista Bay comprise (in decreasing age) the Love Cove Group (Jenness, 1957), the Connecting Point Group (Hayes, 1948) and the Musgravetown Group (Hayes, op. cit.). Whereas the relative ages of these units are generally agreed upon, uncertainty exists as to the nature and significance of the original contact relationships of rocks assigned to the Love Cove and Musgravetown groups. Presently, many of the contacts of these three units are faults (Jenness, 1963; O'Brien, 1987; O'Brien and Blackwood, 1987). North of the study area, the Musgravetown Group passes conformably up into strata of probable early Cambrian age (O'Brien and Knight, 1988).

The present study includes examination of some of the rocks previously assigned to the western belt of the Love Cove Group. These are bounded to the northwest by the Dover Fault. Previous studies (e.g., Blackwood, 1977) have considered their southeast contact with supposedly younger sedimentary rocks of the Musgravetown Group to be a high-angle dislocation, the Howses Cove Fault. As will be described below, the present work provides new evidence that suggests that the western belt of supposed Love Cove Group in the study area is younger than and conformably overlies the local Musgravetown Group rocks.

MUSGRAVETOWN GROUP

Sedimentary rocks exposed along both shores of Content Reach (Figure 2) are here assigned to the Musgravetown Group. Those on the southeast and south shores have previously been placed in this group and were assigned to the Rocky Harbour and Crown Hill formations of Jenness (1963) by O'Brien and Knight (1988). The rocks cropping out on the northwest shore of Content Reach were originally mapped by Younce (1970) as Musgravetown Group, but all subsequent studies have placed them in the Love Cove Group, following Blackwood (1977).

Sandstone, shale and conglomerate of the Musgravetown Group along the southeast shoreline of Content Reach form a little deformed, right-way-up succession that can be divided into four lithological units (Blackwood, 1977; O'Brien and Knight, 1988; O'Brien and Blackwood, 1987, Figure 2). The structurally and stratigraphically highest unit overlies a prominent conglomerate horizon and crops out in the core of a major northeast-plunging syncline in Shatter Cove (see Figure 1). It comprises purplish-green siltstone and sandstone, with subordinate shale and, characteristically, purple- to buff-coloured, crossbedded sandstone, which contains pebbly horizons usually less than 1 m thick (Plate 6). These sandstone beds are highly veined with quartz in many exposures and often weather proud of the surface due to their competent nature. These sandstones and shales are identical in composition and appearance to the rocks immediately below those volcanic rocks on the shores of Content Reach, which are included in the Love Cove Group by Blackwood (1977).

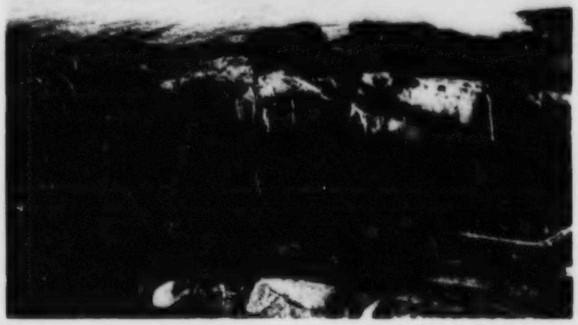

Plate 6. *Interbedded buff sandstone, purple-green siltstone and thin mudstone from the stratigraphically highest unit of the Musgravetown Group, southeast shore, Content Reach. Note the upright slatey cleavage in the siltstone and the quartz veining in the sandstone.*

Primary sedimentary structures are very well preserved in the Musgravetown Group rocks. These include crossbedding, graded-bedding, channels and ripple marks within the sandstones, mud-flake breccias, and spectacular mm- to cm-scale slump structures within many siltstone–mudstone units. Open upright folds with a moderate to weak cleavage (Plate 6) form the main tectonic structures in most exposures. Many exposed contacts with the Love Cove Group volcanic rocks are faults, but conformable, unfaulted boundaries are exposed at the southwest end of Content Reach and on Shoal Island (A and B on Figure 2). A narrow zone of interbanded volcanic rocks and silty sandstone, 1 to 2 m wide, occurs at the contact, and the sedimentary rocks consistently young upward into the overlying volcanic rocks. The Musgravetown Group rocks are more highly cleaved than in the exposures farther to the southeast, but they are otherwise identical. The so-called Howses Cove Fault (as shown by Blackwood, 1977) does not exist, although a small northeast-trending fault forms the contact between sedimentary and volcanic rocks on the coast (Figure 2).

LOVE COVE GROUP

The volcanic rocks in the study area, originally mapped as Love Cove Group, form the terminus of a 100-km-long belt, which is bounded to the northwest by the Dover Fault. Exposures in the area are intensely cleaved, colour-banded volcanic rocks, including acid to intermediate crystal tuffs, lithic tuffs, breccias, agglomerates and (rarely) rhyolite flows up to 25 m thick. Minor mafic horizons occur throughout the region. Way-up criteria are not preserved as the banding is apparently transposed into the steeply dipping tectonic cleavage; mm- to cm-scale isoclinal intrafolial folds of banding are common in areas of lower strain. Volcanic fragmentary material is strongly wrapped and often flattened by the tectonic foliation. A southeast to northwest increase in intensity in deformation occurs toward the Dover Fault and the rocks become increasingly phyllonitic. They still retain some primary lithological colour banding, but tend to take on a secondary pale green or brown colouration. In places, previous authors have mapped phyllonitic volcanic rocks as mylonitic granite (e.g., Hare Bay region; Blackwood, 1977).

INTRUSIVE ROCKS

Granites like those found in the Gander Zone are absent; however, late-stage pegmatoid veins, up to 20 cm wide, are preserved in a few locations around Shoal Bay and Lockers Bay. These crosscut most of the tectonic fabrics.

Narrow, undeformed dykes of greenish-black diabase occur in a few places in the study area. They are crosscut by late brittle faults, but postdate all other structures in the area. Similar dykes are found throughout the Gander Zone, where they pre-date the ?Devonian Newport Granite (e.g., Jayasinghe, 1978).

STRUCTURAL GEOLOGY

The intensity and complexity of deformation increases northwestward within the rocks of the Avalon Zone, and appears to be controlled by proximity to the Dover Fault. A single northeast-trending, steeply dipping slaty cleavage is moderately to weakly developed within the little-deformed clastic sedimentary rocks of the Musgravetown Group exposed on the southeast shore of Content Reach (Plate 6). It is associated with gentle to close, shallowly northeast- or southwest-plunging folds of km scale (e.g., Blackwood, 1978; O'Brien and Blackwood, 1987); minor folds are rare. Conglomerate horizons are little-deformed and original sedimentary imbrication fabrics are still preserved. There is no clear tectonic lineation in this region. The cleavage intensifies toward the overlying volcanic rocks (Love Cove Group of Blackwood, 1977) and, on the northwest side of Content Reach, open to tight minor folds are common, especially within more competent sandstone units; these folds consistently verge toward the anticline farther to the southeast (Figures 2 and 6). In the same exposures, a second set of open to tight folds ('Later Ductile' structures) deform the slatey cleavage (an 'Earlier' structure) and consistently display the reverse sense of vergence (e.g., antiform to the northwest, Figure 6). The intensity of strain rises sharply in the region around the contact between the Musgravetown and Love Cove groups. A steep, south-plunging lineation is developed on the Early cleavage planes a few tens of metres below the contact. Minor early folds tighten and their hinges become intensely curvilinear about the steeply plunging lineation (Figure 6). The Later folds also tighten locally, developing a fine axial-planar crenulation cleavage, and they can be mistaken for early structures in some exposures. However, they always fold the Early mineral lineation.

In the lower parts of the Love Cove Group, the Early steeply south-plunging lineation is prominent, and is commonly defined by highly elongate volcanic clasts. S-C fabrics and asymmetric wrapping of porphyroclasts give northwest-side-up senses of shear (Plate 7). Most minor Early fold axes lie parallel to the lineation, but rare examples of eye structures (Quinquis *et al.*, 1978) suggest that they possess a sheath-fold geometry (Figure 6). Later ductile folds are rare in the lower parts of the Love Cove Group.

The Early lineation gradually rotates anticlockwise (viewed northwest) through the vertical and round into a shallowly plunging or sub-horizontal, northeast-southwest orientation as the Dover Fault is approached (Figure 6). In the central part of the Love Cove Group, where the lineation plunges moderately northeast, asymmetric wrapping of volcanic clasts (e.g., Plate 8) consistently indicates a sinistral and northwest-side-up sense of shear (Figure 6). In the 200 to 600 m of rock nearest to the Dover Fault, Later Ductile folds, together with an associated steeply dipping crenulation fabric, become apparent. The folds are mostly on a scale of centimetres, or less, and are strongly curvilinear about a sub-horizontal northeast trend (Figure 6); they refold the early lineation. In the same zone, asymmetric wrapping fabrics now indicate dextral senses of shear (Figure 6) and it is proposed that this overprints the earlier sinistral displacement. Three important observations support this suggestion. First, the Late Ductile folds always show dextral senses of vergence as their hinges pass through the vertical (Figure 6). Secondly, a dextral Early movement is incompatible with a northwest-side-up sense of displacement, given the anticlockwise rotation of the mineral lineation (Figure 6). Finally, within a few hundred metres of the Dover Fault, volcanic rocks are intensely sheared, greenish-brown phyllonites, which strongly suggest the presence of a low-grade, high-strain zone (cf. Blackwood, 1977).

Thus, it is proposed that an Early phase of sinistral transpression, which developed during ?low greenschist-facies

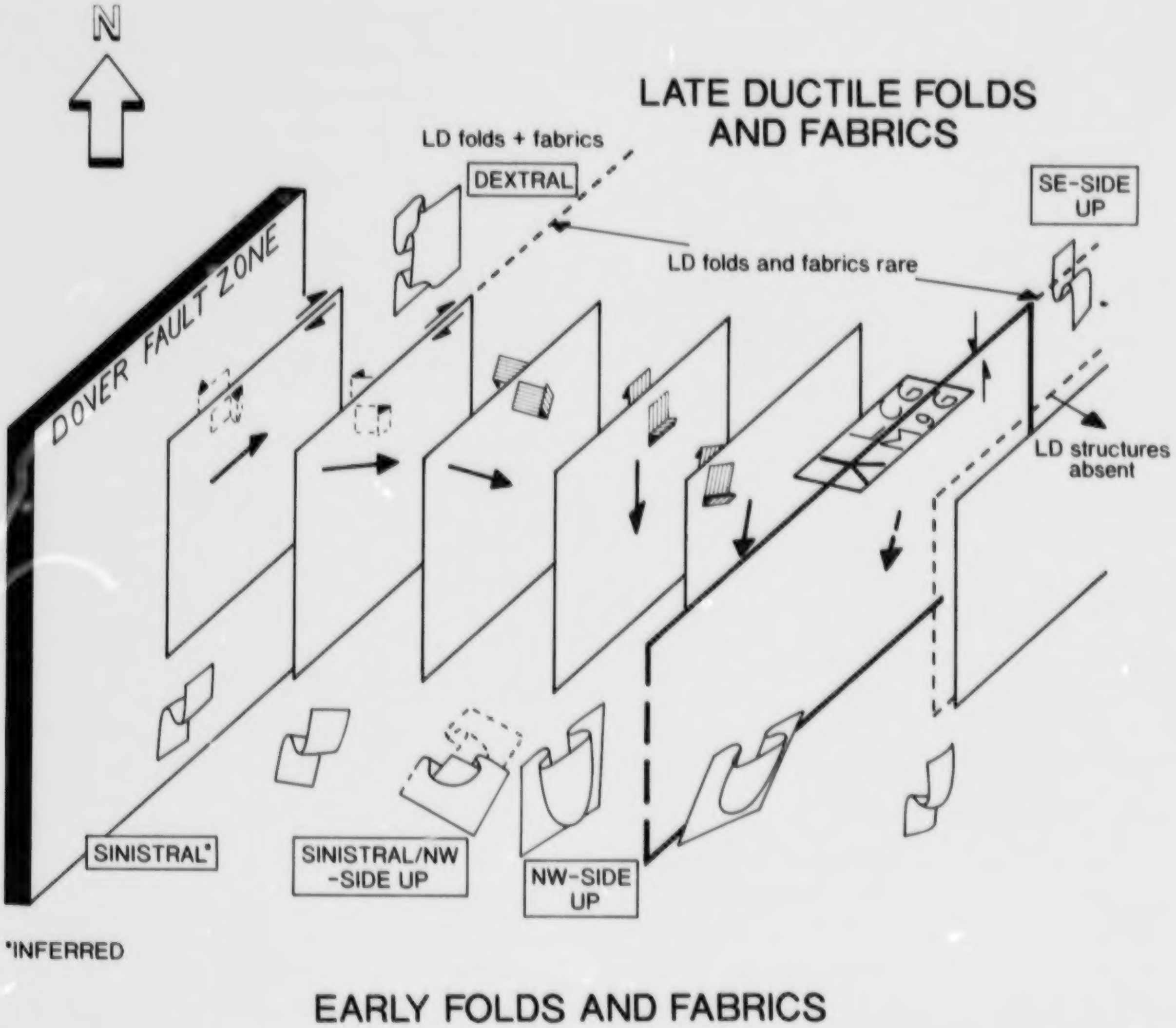
N
LATE DUCTILE FOLDS AND FABRICS
LD folds + fabrics
DEXTRAL
SE-SIDE UP
LD folds and fabrics rare
DOVER FAULT ZONE
LCG
MgG
LD structures absent
SINISTRAL*
SINISTRAL/NW -SIDE UP
NW-SIDE UP
*INFERRED
EARLY FOLDS AND FABRICS

Figure 6. *3-dimensional diagram summarizing the structure of the northwest Avalon Zone, Bonavista Bay. The planes with solid arrows represent the regional tectonic cleavage and lineation respectively. Early and Late Ductile fold geometries are shown along the base and top of the diagram. Early shear sense is shown by the 3-D lined shear couple arrows; Late Ductile (LD) shear sense is shown by the solid-headed 2-D shear couple arrows. MgG and LCG = the Musgravetown and Love Cove groups respectively; note younging arrow across contact defined by thick line.*

metamorphism, is overprinted by dextral Later Ductile movements (?lower grade) in a narrow belt adjacent to the Dover Fault. The rotation of the lineation is probably a feature of the earlier deformation, reflecting an increasing component of sinistral shear toward the original northwest boundary of the Avalon Zone. Similar lineation patterns are widely recognized within transpression zones elsewhere (e.g., Sanderson and Marchini, 1984; Holdsworth, 1989; Holdsworth and Strachan, *in press*).

Faults ('Late Brittle' structures) are mostly northeast trending and have steep dips. They are particularly common along the contact of the Musgravetown and Love Cove groups and in the immediate vicinity of the Dover Fault. Many are associated with belts up to 100 m wide of greenish-grey rocks, which are commonly highly folded and/or brecciated. The folds have brittle deformation styles and are mostly steeply plunging with dextral senses of vergence. Minor fault offsets are also predominantly dextral. Thus, it is suggested that Late Ductile dextral movements were postdated by Late Brittle dextral faulting and associated minor folding. The actual age of these two sets of movements is discussed later.

Plate 7. *Sheared crystal tuff of the Love Cove Group viewed in vertical surface parallel to steeply plunging lineation, south coast of Hare Bay. Centimetre-scale shear bands (an S-C fabric) give northwest-side-up senses of movement.*

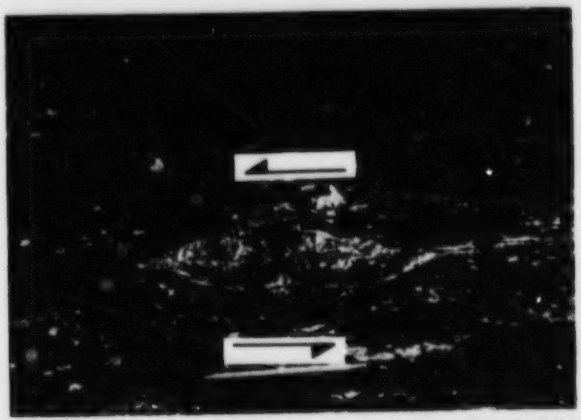

Plate 8. *Sheared volcanic breccia, Love Cove Group, 1 km west of location A in Figure 2. Asymmetric wrapping of clasts gives a sinistral sense of shear.*

DISCUSSION

NATURE OF THE GANDER–AVALON BOUNDARY

In the Hare Bay–Dover region (Figure 2), the Gander–Avalon boundary is most often marked by a Late Brittle fault. In three locations (1, 2 and 3 in Figure 2), brownish-green and grey phyllonites, interpreted to be derived from Love Cove Group volcanic rocks, are in contact with green phyllonites having pink sheared granitic layers that are interpreted to be derived from the Hare Bay Gneiss and Dover Fault Granite veins. The boundary is sharp and concordant and is interpreted as a ductile fault formed during the Late Ductile deformation. The most accessible exposure of the contact lies on the northwest side of a narrow peninsula northeast of the Hare Bay Municipal Park. The rocks here have been previously and incorrectly described as mylonitic Dover Fault Granite (e.g., Blackwood, 1977).

GANDER–AVALON CORRELATIONS

The present study confirms the fundamental differences in rock types, metamorphic grade and intrusive history that are apparent across the Gander–Avalon boundary. However, in the region close to the boundary, both zones preserve a three-phase kinematic history comprising: Early Ductile sinistral transpression (northwest-side-up), Later Ductile dextral transpression, and finally Later Brittle dextral faulting. The latter two phases are associated with displacements along the Dover Fault, with the main Gander–Avalon boundary being a ductile dextral fault. In the absence of any evidence to the contrary, it is here proposed that the earlier sinistral events may also be correlatives. This structural linkage, first recognized by Caron and Williams (1988 a, b) pre-dates the Dover Fault, and may relate to the original juxtaposition of the Gander and Avalon zones. Thus, the Dover Fault may have reactivated an earlier sinistral boundary. The complete lack of other correlatable features across the boundary implies that lateral displacements are large, whereas the marked differences in metamorphic grade suggests that significant and probably rapid uplift of the Gander Zone has occurred (cf. Dallmeyer *et al.*, 1981).

TIMING OF EVENTS

The present study suggests that the Cape Freels Granite was intruded synchronously with the later stages of Early Ductile sinistral transpression in the Gander Zone. The Lockers Bay Granite appears to be slightly later, and is thought to have been intruded during the early stages of Late Ductile dextral movements. The unfoliated Middle Brook Granite appears to have been emplaced subsequent to all ductile deformation.

It is the author's view that much of the ductile deformation, metamorphism and plutonism in the Gander Zone occurred during a relatively short period. However, it is conceivable that the igneous protoliths of the earliest gneisses, the early isoclines and the migmatitic fabrics they fold in the metasedimentary rocks and the amphibolites, could be significantly earlier features.

If the correlation of events into the Avalon Zone is correct, all deformation in the Musgravetown and Love Cove groups in the study area is Paleozoic. However, the possibility that the Dover Fault, or its sinistral precursor, reactivated an earlier, deep-seated Avalonian structure cannot be discounted.

Geochronological studies to determine the age of principal orogenic phases in northeast Newfoundland are in progress. The magmatic and metamorphic character of the northeast Gander Zone is analogous in some respects to that of the Hermitage Flexure, and these similarities have led to the extrapolation of the Gander Zone into parts of southern Newfoundland (e.g., Colman-Sadd *et al.*, 1990). Given the widespread Silurian orogenesis in the latter area (e.g.,, Dunning *et al.*, 1990; O'Brien *et al.*, 1991) it is likely that a significant component of the geological history described here from northeast Newfoundland is Silurian (cf. Currie and Piasecki, 1989). The extent of Acadian (Devonian) ductile deformation in this part of the Appalachian Orogenic belt is uncertain; it is possible that the later stages of Late Ductile shearing are this age.

AGE OF BRITTLE FAULTING

Many of the Late Brittle faults appear to have formed preferentially within the regions affected by low-grade Late Ductile shearing, most obviously, the Dover Fault shear zone. This has led some authors (e.g., Caron and Williams, 1988a, b) to imply that significant amounts of faulting are simply continuations of the earlier ductile dextral movements as the fault zone passed through the brittle-ductile transition during uplift and erosion. Whereas this may have happened in some instances, regional field relationships suggest that much of the brittle faulting is significantly later and that the coincidence with earlier ductile shear zones is therefore a feature of reactivation. In particular, the intrusion of the unfoliated Newport Granite postdates ductile, but pre-dates brittle dextral movements along the Dover Fault Zone. This granite has an Rb−Sr whole-rock date of 332 ± 42 Ma, which has been interpreted as an intrusion age (Bell *et al.*, 1979). Whereas a high precision U−Pb date is clearly required, the existing date means that an Alleghanian age of brittle movement cannot as yet be discounted in the Bonavista Bay region.

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REFERENCES

Anderson, M.M., Bruckner, W.D., King, A.F. and Maher, J.B.
1975: The late Proterozoic 'H.D. Lilly Unconformity' at Red Head, Northeast Avalon Peninsula, Newfoundland. American Journal of Science, Volume 27, pages 1012-1027.

Bell, K., Blenkinsop, J. and Strong, D.F.
1977: The geochronology of some granite bodies from eastern Newfoundland and its bearing on Appalachian evolution. Canadian Journal of Earth Sciences, Volume 14, pages 456-476.

Bell, K., Blenkinsop, J., Berger, A.R. and Jayasinghe, N.R.
1979: The Newport Granite: Its age, geological setting and implications for the geology of northeastern Newfoundland. Canadian Journal of Earth Sciences, Volume 14, pages 456-476.

Blackwood, R.F.
1976: The relationship between the Gander and Avalon Zones in the Bonavista Bay region, Newfoundland. M.Sc. thesis, Memorial University of Newfoundland, St. John's, 156 pages.

1977: Geology of the east half of the Gambo (2D/16) map area and the northeast portion of the St. Brendan's (2D/13) map area, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-5, 20 pages.

1978: Northern Gander Zone, Newfoundland. *In* Report of Activities for 1977. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-1, pages 72-79.

Blackwood, R.F. and Kennedy, M.J.
1975: The Dover Fault: western boundary of the Avalon Zone in northeastern Newfoundland. Canadian Journal of Earth Sciences, Volume 12, pages 320-325.

Blenkinsop, J., Cucman, P.F. and Bell, K.
1976: Age relationships along the Hermitage Bay-Dover Fault system, Newfoundland. Nature, Volume 262, pages 377-378.

Caron, A. and Williams, P.F.
1988a: The multistage development of the Dover Fault Zone in northeastern Newfoundland: the late stages. Geological Association of Canada−Mineralogical Association of Canada−Canadian Society of Petroleum Geologists, Joint Annual General Meeting, Program with Abstracts, Volume 13, page A17.

1988b: The kinematic indicators of the Love Cove Group in Northeastern Newfoundland. Geological Association of Canada−Mineralogical Association of Canada−Canadian Society of Petroleum Geologists Joint Annual General Meeting, Program with Abstracts, Volume 13, page A17.

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. (Compilers)
1990: Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-01.

Currie, K.L. and Piasecki, M.A.J.
1989: Kinematic model for southwestern Newfoundland based upon Silurian sinistral shearing. Geology, Volume 17, pages 938-941.

Dallmeyer, R.D., Blackwood, R.F. and Odom, A.L.
1981: Age and origin of the Dover Fault: tectonic boundary between the Gander and Avalon Zones of the northeastern Newfoundland Appalachians. Canadian Journal of Earth Sciences, Volume 18, pages 1431-1442.

Dallmeyer, R.D., Hussey, E.H., O'Brien, S.J. and O'Driscoll, C.F.
1983: Chronology of metamorphism in the western Avalon Zone, Newfoundland: Evidence from ^{40}Ar/^{39}Ar incremental release ages of phyllites. Canadian Journal of Earth Sciences, Volume 20, pages 355-361.

Dunning, G.R., O'Brien, S.J., Colman-Sadd, S.P., Blackwood, R.F., Dickson, W.L., O'Neill, P.P. and Krogh, T.E.
1990: Silurian Orogeny in the Newfoundland Appalachians. Journal of Geology, Volume 98, pages 895-913.

Durling, P.W., Bell, J.B. and Fader, G.B.J.
1987: The geological structure and distribution of Paleozoic rocks on the Avalon Platform, offshore Newfoundland. Canadian Journal of Earth Sciences, Volume 24, pages 1412-1420.

Hanmer, S.
1981: Tectonic significance of the northeastern Gander Zone, Newfoundland: an Acadian ductile shear zone. Canadian Journal of Earth Sciences, Volume 18, pages 120-135.

Hayes, A.O.
1948: Geology of the area between Bonavista and Trinity Bays, eastern Newfoundland. Geological Survey of Newfoundland Bulletin 32, part 1, pages 1-37.

Holdsworth, R.E.
1989: The Start-Perranporth Line: a Devonian terrane boundary in the Variscan orogen of southwest England? Geological Society of London, Volume 146, pages 419-421.

1990: Progressive deformation structures associated with ductile thrusts in the Moine Nappe, Sutherland, north Scotland. Journal of Structural Geology, Volume 12, pages 443-452.

Holdsworth, R.E. and Strachan, R.A.
In press: An interlinked system of ductile strike-slip and thrusting formed by Caledonian sinistral transpression in northeastern Greenland. Geology.

Hughes, C.J.
1970: The late Precambrian Avalonian Orogeny in Avalon, southeast Newfoundland. American Journal of Science, Volume 258, pages 183-190.

Hutchinson, R.D.
1962: Cambrian stratigraphy and trilobite faunas of southeastern Newfoundland. Geological Survey of Canada Bulletin, Volume 35, 156 pages.

Hutton, D.H.W.
1988: Granite emplacement mechanisms and tectonic controls: inferences from deformation studies. Transactions of the Royal Society of Edinburgh, Earth Sciences, Volume 79, pages 245-255.

Jayasinghe, N.R.
1978: Geology of the Wesleyville (2F/5) map areas, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-5, 11 pages.

Jayasinghe, N.R. and Berger, A.R.
1976: On the plutonic evolution of the Wesleyville area, Bonavista Bay, Newfoundland. Canadian Journal of Earth Sciences, Volume 13, pages 1560-1570.

Jenness, S.E.
1957: Gander Lake (east half), Newfoundland. Geological Survey of Canada, Map 5-1957.

1963: Terra Nova and Bonavista map areas, Newfoundland. Geological Survey of Canada, Memoir 327, 184 pages.

Keen, C.F., Kean, M.J., Nichols, R., Reid, I., Stockmal, G., Colman-Sadd, S.P., O'Brien, S.J., Miller, H., Quinlan, G., Williams, H. and Wright, J.
1986: Deep seismic reflection profile across the northern Appalachians. Geology, Volume 14, pages 141-145.

Kennedy, M.J. and McGonigal, M.H.
1972: The Gander Lake and Davidsville Groups of northeastern Newfoundland: new data and geotectonic implications. Canadian Journal of Earth Sciences, Volume 9, pages 452-459.

King, A.F.
1980: The birth of the Caledonides: late Precambrian rocks of the Avalon Peninsula, Newfoundland and their correlatives in the Appalachian–Caledonian orogen. *In* The Caledonides in the U.S.A. *Edited by* D.R. Wones. Department of Geological Sciences, Virginia Polytechnical Institute and State University Memoir, Volume 2, pages 3-8.

Krogh, T.E., Strong, D.F., O'Brien, S.J. and Papezik, V.S.
1988: Precise U–Pb age dates of zircons from the Avalon terrane in Newfoundland. Canadian Journal of Earth Sciences, Volume 25, pages 442-459.

Lilly, H.D.
1966: Late Precambrian and Appalachian tectonics in the light of submarine exploration on the Great Bank of Newfoundland and in the Gulf of St. Lawrence. American Journal of Science, Volume 264, pages 569-574.

McCartney, W.D.
1967: Whitbourne map-area, Newfoundland. Geological Survey of Canada, Memoir 341, 135 pages.

Nur, A., Ron, H. and Scotti, O.
1989: Kinematics and mechanics of tectonic block rotations. Tectonics, Volume 8, pages 31-46.

O'Brien, S.J.
1987: Geology of the Eastport (west half) map area, Bonavista Bay, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 257-270.

O'Brien, S.J. and Blackwood, R.F.
1987: St. Brendan's (2C/13), Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 87-55.

O'Brien, S.J. and Knight, I.
1988: The Avalonian geology of southeast Bonavista Bay: portions of the St. Brendan's (2C/13) and Eastport (2C/12) map areas. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 193-205.

O'Brien, S.J., Wardle, R.J. and King, A.F.
1983: The Avalon Zone: A Pan-African terrane in the Appalachian Orogen of Canada. Geological Journal, Volume 18, pages 195-222.

O'Brien, S.J., Strong, D.F. and King, A.F.
1990: The Avalon Zone type area: southeastern Newfoundland Appalachians. *In* Avalonian and Cadomian Geology of the North Atlantic. *Edited by* R.A. Strachan and G.K. Taylor. Blackies and Son, Ltd., Glasgow, pages 166-193.

O'Brien, S.J., O'Brien, B.H., O'Driscoll, C.F., Dunning, G.R., Holdsworth, R.E. and Tucker, R.
1991: Silurian orogenesis and the northwest limit of Avalonian rocks on the Hermitage Flexure, Newfoundland Appalachians. Geological Society of America, Northeast-Southeast Combined Annual Meeting; Volume 23, number 1.

O'Neill, P.P.
1987: Geology of the west half of the Weir's Pond (2E/1) map area. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 271-281.

O'Neill, P.P. and Knight, I.
1988: Geology of the east half of the Weir's Pond (2E/1) map area and its regional significance. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 165-176.

O'Neill, P.P. and Lux, D.
1989: Tectonothermal history and ^{40}Ar/^{39}Ar geochronology of northeastern Gander Zone, Weir's Pond area (2E/1). *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 131-139.

O'Neill, P.P. and Blackwood, R.F.
1989: A proposal for revised stratigraphic nomenclature of the Gander and Davidsville groups and the Gander River Ultrabasic Belt, of northeastern Newfoundland. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 127-130.

Quinquis, H., Audren, C., Brun, J.P. and Cobbold, P.R.
1978: Intense progressive shear in the Isle de Groix blueschists and compatibility with subduction or obduction. Nature, Volume 273, pages 43-45.

Sanderson, D.J. and Marchini, W.R.D.
1984: Transpression. Journal of Structural Geology, Volume 6, pages 449-458.

Strong, D.F., O'Brien, S.J., Taylor, S.W., Strong, P.G. and Wilton, D.
1978: Geology of the Marystown (1M/3) and St. Lawrence (1L/14) map areas, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-8, 31 pages.

Tchalenko, J.S.
1970: Similarities between shear zones of different magnitudes. Geological Society of America Bulletin, Volume 81, pages 1625-1640.

Tuach, J.
1987: The high-silica magmatic/metallogenic system and associated post-tectonic granites, southeast Newfoundland. Ph.D. thesis, Memorial University of Newfoundland, St. John's, 455 pages.

Wilcox, R.E., Harding, T.P. and Seely, D.R.
1973: Basic wrench tectonics. American Association of Petroleum Geologists Bulletin, Volume 57, pages 74-96.

Williams, H.
1968: Wesleyville, Newfoundland. Geological Survey of Canada, Map 1227A.

1979: Appalachian Orogen in Canada. Canadian Journal of Earth Sciences, Volume 16, pages 792-807.

1984: Miogeoclines and suspect terranes of the Caledonian−Appalachian Orogen: tectonic patterns in the North Atlantic region. Canadian Journal of Earth Sciences, Volume 21, pages 887-901.

Williams, H., Colman-Sadd, S.P. and Swinden, H.S.
1988: Tectonic-stratigraphic subdivisions of central Newfoundland. *In* Current Research, Part B. Geological Survey of Canada, Paper 88-1B, pages 91-98.

Williams, H., Kennedy, M.J. and Neale, E.R.W.
1974: The northeastward termination of the Appalachian Orogen. *In* The Ocean Basins and Margins, Volume 2, The North Atlantic. *Edited by* A.E.M. Nairn and F.G. Stehli. New York, Plenum Press, pages 79-123.

Wonderley, P.F. and Neuman, R.B.
1984: The Indian Bay Formation: fossiliferous Early Ordovician volcanogenic rocks in the northern Gander Terrane, Newfoundland and their regional significance. Canadian Journal of Earth Sciences, Volume 21, pages 525-532.

Younce, G.B.
1970: Structural geology and stratigraphy of the Bonavista Bay region, Newfoundland. Ph.D. thesis, Cornell University Ithaca, New York, 188 pages.

Current Research (1991) *Newfoundland Department of Mines and Energy,*
Geological Survey Branch, Report 91-1, pages 127-140

TOWARD AN INTEGRATED DATABASE FOR NEWFOUNDLAND GRANITOID SUITES: A PROJECT OUTLINE AND PROGRESS REPORT

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Newfoundland Mapping Section

SUMMARY

This report summarizes work completed, or in progress, as part of a project to integrate and interpret petrological and geochemical data from Newfoundland plutonic suites; it also provides an outline of future plans. The objectives are to develop and release a representative geochemical database for the island, to interpret these data in terms of petrogenesis and mineral potential, and to determine the relationships of plutonic associations to tectonic evolution. In this context, it is anticipated that integrated research involving isotopic and mineralogical studies can be continued in cooperation with outside researchers.

Information in Departmental computer archives has been assembled into a core database, and a variety of other data are collated for future incorporation. The core database is currently being checked and verified to eliminate errors in the location and classification of records. It is presently dominated by (mostly post-1980) data from southern Newfoundland, with lesser amounts of older data from eastern Newfoundland. Re-analysis of a subset of samples from a 1974 survey has raised doubts about the reliability of many of these older results; these samples have now been re-analyzed, with an expanded trace-element suite. Re-analysis will likely be required for other areas surveyed in the 1970's.

Under the Canada–Newfoundland Cooperation Agreement on Mineral Development 1990-1995, new field work and geochemical sampling is planned for many intrusions that are presently unrepresented, and to improve coverage in other areas. Re-analysis of older sample populations will continue as required, and acquisition of new data for a range of additional elements (e.g., REE) will be initiated. Multidisciplinary studies initiated over the last two years will be continued.

INTRODUCTION

Approximately one third of the island of Newfoundland is underlain by intrusive rocks that broadly form part of the 'granitoid clan', ranging in composition from diorite to alkali-feldspar granite. Geological mapping over the last 20 years, by various agencies, has resulted in coverage of large areas by 1:100,000- or 1:50,000-scale geological maps. A new 1:1,000,000-scale compilation map was recently released (Colman-Sadd *et al.*, 1990), replacing the earlier compilations by Williams (1967) and Hibbard (1983a).

The new map illustrates a number of changes in the classification of Newfoundland granitoid suites, but such are minor compared to revisions to volcanic and sedimentary sequences and their structural relationships. This reflects the 'natural' emphasis of geological mapping toward 'layered' rocks, which provide most information about structure, and the perception that sedimentary and volcanic sequences have a higher economic potential than many granitoid intrusions. Nevertheless, a considerable amount of petrological and geochemical information has been amassed from granitoid rocks in the course of regional mapping programs, particularly during the Canada–Newfoundland Mineral Development Agreement (MDA), and some Newfoundland granites are considered to have potential for economic mineralization.

With the signing of a new agreement (Canada–Newfoundland Cooperation Agreement on Mineral Development 1990-1995 = AMD 1990-1995) in late 1990, a project was initiated to compile, release and ultimately interpret the large volume of data collected by the Newfoundland Department of Mines and Energy (NDME). In addition to the collation of existing information, this project will also incorporate new work aimed at improving our understanding of the many areas where the present information base is cursory, and at providing a representative database for as much of the island as is feasible. The overall objective is to provide a basis for assessment of the petrogenesis, evolution and mineral potential of many of these suites, and to increase our understanding of their role in the geotectonic development of Newfoundland. This report contains a summary of work conducted on this project to date, and discusses some of the new directions planned for it under AMD 1990-1995, commencing in the 1991–1992 fiscal year. As only preliminary work has been undertaken to date, this

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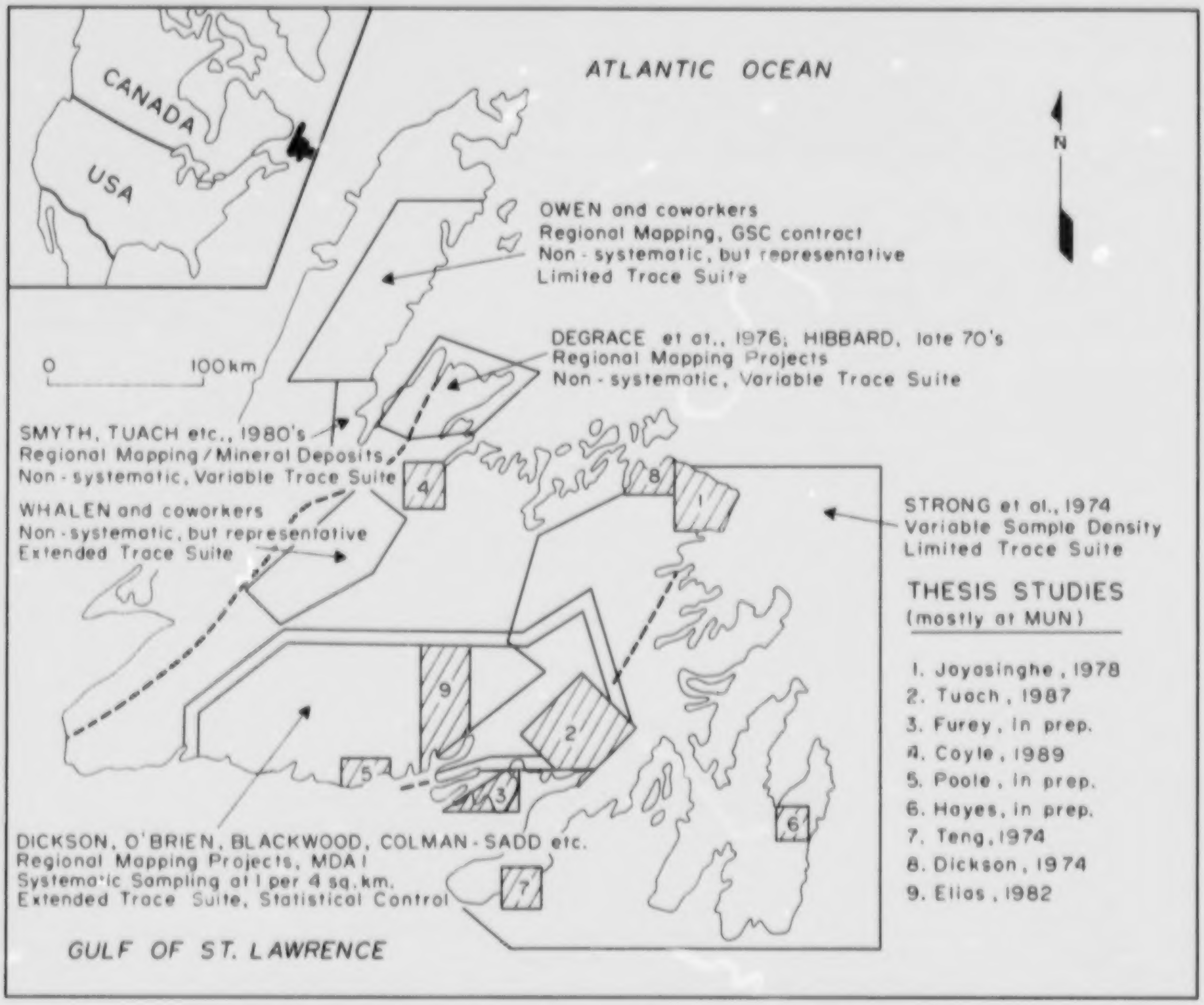
ATLANTIC OCEAN
CANADA
USA
N
0 100km
OWEN and coworkers
Regional Mapping, GSC contract
Non - systematic, but representative
Limited Trace Suite
DEGRACE et al., 1976; HIBBARD, late 70's
Regional Mapping Projects
Non - systematic, Variable Trace Suite
SMYTH, TUACH etc., 1980's
Regional Mapping / Mineral Deposits
Non - systematic, Variable Trace Suite
WHALEN and coworkers
Non - systematic, but representative
Extended Trace Suite
STRONG et al., 1974
Variable Sample Density
Limited Trace Suite
THESIS STUDIES
(mostly at MUN)
1. Jayasinghe, 1978
2. Tuach, 1987
3. Furey, in prep.
4. Coyle, 1989
5. Poole, in prep.
6. Hayes, in prep.
7. Teng, 1974
8. Dickson, 1974
9. Elias, 1982
1
2
3
4
5
6
7
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9
DICKSON, O'BRIEN, BLACKWOOD, COLMAN-SADD etc.
Regional Mapping Projects, MDA I
Systematic Sampling at 1 per 4 sq.km.
Extended Trace Suite, Statistical Control
GULF OF ST. LAWRENCE

Figure 1. *Locations of and approximate areas covered by mapping projects that have contributed or are potential sources for geochemical data from Newfoundland granitoid rocks.*

article is a progress report and project outline, rather than a discussion of selected research topics. For preliminary discussion and interpretation of some of the geochemical data described here, see Dickson *et al.* (1990) and Kerr *et al.* (1990a). For a brief overview of the characteristics of Newfoundland granitoid intrusive suites, see Williams *et al.* (1989).

PREVIOUS STUDIES OF NEWFOUNDLAND GRANITOID ROCKS

Most systematic petrological and geochemical investigations incorporating geochemical studies have been conducted in the last two decades. Some of the most important contributions, and the approximate areas that they cover, are illustrated in Figure 1.

PROJECTS CONDUCTED DURING THE 1970'S

The survey of Strong *et al.* (1974) was the first large-scale application of geochemical and statistical methods to Newfoundland granitoid rocks, and was intended to provide a regional assessment of the mineral potential of those granitoid rocks in eastern Newfoundland. It was based on almost 1300 samples, collected mostly from coastal or roadside exposures. Although a few areas covered by this survey were later investigated in greater detail, the data of Strong *et al.* (1974) remain the only significant public-domain geochemical information for many eastern Newfoundland plutonic suites. The geochemical data were acquired mostly by X-ray fluorescence (XRF) methods, and include only a limited trace-element suite (Zr, Sr, Rb, Zn, Cu, Ba and F). Uranium was subsequently determined by neutron-activation (NAA) methods (Davenport, 1978).

During a similar time-period, a regional mapping project in the Baie Verte area (summarized by DeGrace *et al.*, 1976) produced 180 analyses of volcanic and plutonic rocks, using similar analytical methods to those of Strong *et al.* (1974). With the exception of a small number of analyses, presented by Hibbard (1983b), this 1976 database is the only significant public-domain source of geochemical data from granites in what has subsequently become an important exploration area. In the late 1970's, Elias (1979, 1980) conducted extensive geochemical sampling of granites in south-central Newfoundland, in conjunction with NDME mapping and a thesis study. This project was the first to employ a structured approach to geochemical sampling and mapping large areas of granitoid rocks. In contrast to sporadic sampling patterns determined largely by access (e.g., roads and coastlines), it produced a fairly constant sample density of about 1 per 4 km^2. Geochemical data were released (Colman-Sadd *et al.*, 1981) and are summarized by Colman-Sadd and Swinden (1982). They include a wider range of trace elements than the earlier studies.

PROJECTS CONDUCTED DURING THE 1980'S

The structured approach to sampling developed in the late 1970's was used during mapping of the Ackley granite (Dickson, 1983). The large volume of geographically representative data was used to supplement traditional unit divisions based on petrography, and to assess geochemical zonation patterns within the intrusion (Tuach, 1987).

Throughout the 1980's, much geological mapping under the MDA was focussed on the south coast of Newfoundland (e.g., O'Brien *et al.*, 1986; Dickson *et al.*, 1989). Most of this area is underlain by granitoid rocks, and mapping techniques were similar to those employed in the Ackley granite project. Extensive grid-based geochemical sampling of granitoid rocks accompanied and supplemented mapping programs throughout this area, and also in parts of the central Gander Zone (Blackwood, 1983). As a result of these projects, granitoid plutons in southern Newfoundland are now covered by systematic lithogeochemical sampling, and are probably better known than many in more accessible parts of the province.

OTHER RELEVANT GEOCHEMICAL SURVEYS

The Geological Survey of Canada (GSC) has also examined Newfoundland granitoid rocks. In the 1980's, their focus was the Topsails Intrusive Suite, described by Whalen and Currie (1983). Geochemical data were partially released as part of an open-file report on 'A-type' granites (Whalen *et al.*, 1987). Although the sampling methods differ from that employed by recent NDME projects, there has been a similar emphasis on coupled lithological mapping and the geochemical data are of high quality. Mapping in the Long Range Mountains of western Newfoundland by Owen (1988) as part of a MDA research contract, has recently provided the first regional information on Precambrian granites of this Grenville inlier. Small amounts of geochemical data were also acquired by other GSC and NDME mapping projects in various areas of the province (e.g., Chorlton, 1980).

A number of thesis studies based on Newfoundland granites have been conducted at Memorial University and other institutions. Most have been at the B.Sc or M.Sc level, and are consequently of local emphasis, being focussed on a single intrusion or a portion thereof. Others (e.g., Tuach, 1987; Poole, *in preparation*) mostly utilize geochemical data collected via Departmental mapping programs. However, some studies conducted during the late 1980's (e.g., Furey, *in preparation;* Coyle, 1989) promise to be sources of new high-quality geochemical data for some plutons and/or correlative felsic volcanic suites.

VARIATIONS IN THE SPECTRUM AND QUALITY OF GEOCHEMICAL DATA

The changes in sampling methods over the years are mirrored by changes in analytical techniques and capabilities. Most major- and trace-element data are now acquired by atomic absorption (AA) and inductively-coupled plasma (ICP) spectroscopic methods via the NDME laboratory, which allows precision and accuracy to be monitored closely from year to year. Trace elements include several of economic significance (e.g., Mo, Li, Be, F, U and Ag) and some used in classification and modelling (e.g., Ga, Y, Nb, Th, Ce). Few, if any, of these elements were determined on a routine basis during the early 1970's, when most analytical work was contracted to outside agencies. Surveys conducted in the late 1970's and earliest 1980's fall between these extremes, and typically include a mixture of NDME and external contract data. The range of analytical techniques and their precision create some problems in comparison of data, and steps must be taken to upgrade some of the early analyses to current standards (see below).

ASSEMBLY OF A GEOCHEMICAL DATABASE FOR NEWFOUNDLAND GRANITOID ROCKS

OVERVIEW OF CONTENTS

Commencing in 1987, data held in various NDME archives were assembled into a single, large computer file, using the SPSS-X software package. This task was completed in 1988 (Butler, 1988) and the resultant database of about 4500 records is the starting point for this project. The initial priorities were to develop a standardized file format and classification system, and problems inherent in the data themselves were largely set aside for later resolution. Data are presently stored on the Departmental microcomputer.

The data collected from southern Newfoundland intrusions in the late 1970's and early 1980's far outweigh all other material. The data from Strong *et al.* (1974) are the second largest contributor and are the only source for much of eastern Newfoundland. All other sources are minor contributors, and some of the mapping projects located in Figure 1 are presently unrepresented in the database. This is because, prior to the late 1970's, relatively small amounts of geochemical data were not routinely transferred to the computer archives. Figure 2 shows the distribution of the

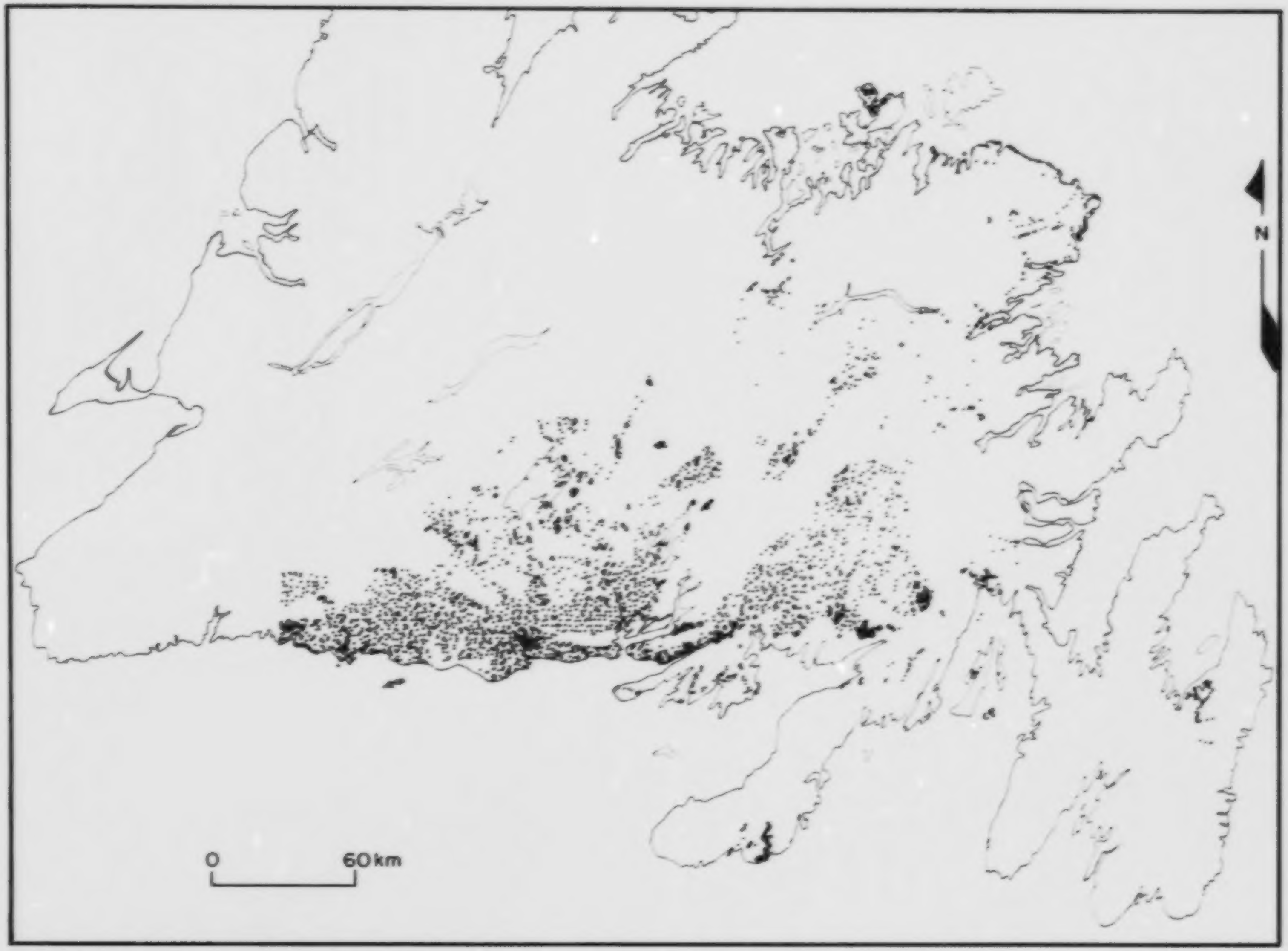

Figure 2. *A computer-generated map showing the geographic distribution of records currently held in the core granitoid database. Note the dominance of data from southern and parts of eastern Newfoundland.*

samples across the Island (compare with Figure 1). It illustrates, in a striking manner, the contrasts in both sample density and sampling patterns between earlier and more recent projects.

Each record in the database consists of identification (both laboratory number and original field number), location and field information, and available geochemical results. Records are grouped using a classification variable, termed the 'pluton number', which denotes the intrusion or plutonic suite in question. This number is derived from the empirical numbering system utilized by Hayes *et al.* (1987) in their summary map of Newfoundland granites.

The term 'pluton' is not used in a literal sense, as the scale of such divisions varies greatly and, in many respects, it is an unsatisfactory term for this classification variable. However, it is retained (in quoted format) in this report. The numbering system has itself developed over several years of informal usage, and hence has little geographic or stratigraphic 'order'. Table 1 lists all the 'plutons' currently numbered and the number of records available for each. For locations of these 'plutons', see the summary map of Hayes *et al.* (1987).

As mentioned above, there are many variations in the spectrum and quality of geochemical data. This applies mostly to trace-element data, but there are also many inconsistencies in major-element analyses; e.g., discrete FeO and Fe_2O_3 analyses versus total iron as either FeO or Fe_2O_3. No distinction is made between analytical methods, although there are large variations in the precision and accuracy of some elements; e.g., Ce (XRF) is well known to be intrinsically less reliable than Ce (ICP). Although UTM coordinates are ubiquitous, other information such as texture, mineralogy, colour, alteration etc., have been recorded to different degrees in different projects. Some recent projects have subdivided records by map unit. Most older data are not subdivided beyond the 'pluton' level.

In the initial concept for this project, incorporation of data collected from Geological Survey of Canada projects and university researchers was proposed. However, the consistency problems noted above, based on the authors' experiences, are likely to be formidable. At present, all external information of this type is being maintained as separate files.

The database discussed above will form the core for all future assembly of geochemical data. Some existing Departmental data has already been assembled as separate files (e.g., Baie Verte Peninsula and White Bay area data) but this will not be added until the core database has passed an exhaustive checking procedure. Similarly, data from limited sampling and mapping conducted during the 1989 and 1990 field seasons (Kerr, 1989, 1990; see below) are also being held in reserve as separate files. Data continue to accumulate from a variety of sources; for example, 1990 field work in several areas of peralkaline igneous rocks (Miller, 1990) will soon fill some significant gaps in our information base.

WORK CURRENTLY IN PROGRESS

The first priority is to eliminate, as far as is possible, all problems related to sample identification and classification. Some are obvious and easily rectified. For example, suspicions were quickly aroused when the very small Piccaire granite of the Baie d'Espoir area was apparently represented by over 100 records, and it was soon established that most belonged to another suite, which had been miscoded. However, not all classification problems are as glaring as this example.

The present checking procedure involves producing sample location maps (corresponding to 1:250,000-scale NTS sheets) where individual 'plutons' are represented by discrete symbols and/or colours. This allows their locations to be checked against the outcrop patterns of their units, and also helps to eliminate any errors in UTM coordinates. Some intensively studied and sampled areas will probably eventually require location checking at a scale of 1:100,000 or greater. In the process, one of us (JH) is developing plotting routines that will be of use in future assessment of spatial geochemical variations (see below).

For these data to be useful on the scale of an individual intrusion or plutonic suite, division into lithological and/or geographical subunits is important. The second phase of the checking procedure involves the plotting of data for a specific 'pluton' at a scale that allows verification of subunits, or their introduction if not already present. Naturally, some 'plutons' cannot be subdivided on either basis. A related problem involves the methodology of unit definition, as some workers (e.g., Tuach, 1987) have utilized definitions based on geochemistry, rather than the lithological and geographical features that are the foundation of stratigraphic nomenclature.

There is also a need to eliminate samples of rock types that do not strictly belong in a database mainly composed of plutonic rocks. The principal rock types are migmatites, hornfelses and assorted country-rock types, which have been sampled during regional mapping and included with granitoid data. Fortunately, the variable 'Rocktype', comprising a 4-letter code, is present for most records and is fairly standard in usage. It is also desirable to identify samples that are strongly mineralized; some of these can be picked out via coded rock type (e.g., 'vein' or 'greisen'), but others may have to be identified via strongly anomalous geochemistry and then verified by original field descriptions.

Once basic questions of identification and classification are resolved, it will be necessary to locate and correct problems with the geochemical data themselves. Post-1978 data has already gone through double-entry verification, during keypunching at Newfoundland and Labrador Computer Services (NLCS), and most geologists working with such data perform their own checks. In the case of older data, substantial re-analysis is planned, and verification prior to incorporation of replacement data will be possible.

Table 1. A listing of all the 'plutons' currently assigned classification numbers, and the number of records presently contained in the core granitoid database. Note that many of the names, introduced by Hayes *et al.* (1987), are of an informal nature (regardless of any capitalization) and subject to revisions

Pluton Number	Name of Unit or Plutonic Suite	Valid Records	Percent of Data
1	Piccaire Granite	21	0.45
2	Gaultois Granite	150	3.21
3	Northwest Cove Granite	24	0.51
4	Straddling Granite	26	0.56
5	Northwest Brook Complex	200	4.28
6	Dolland Bight Granite	31	0.66
7	North Bay Granite Suite	793	16.98
8	Missing Island Granodiorite	6	0.13
9	Long Pond Diorite	4	0.09
10	Rocky Bottom Tonalite	15	0.32
11	Matthews Pond Granodiorite	19	0.41
12	Round Pond Gabbronorite	10	0.21
13	Partridge Berry Hill Granite	73	1.56
14	Through Hill Granite	23	0.49
15	Ackley Granite Suite	587	12.57
16	Eastern Meelpaeg Complex	26	0.56
17	Mt. Sylvester Granite	99	2.12
18	Avalon Straddling Granite	7	0.15
19	Burgeo Intrusive Suite	711	15.22
20	Avalon meta-igneous rocks		
21	Simmons Brook Batholith	24	0.51
22	Kepenkeck Granite		
23	Tolt Granite		
24	Meta Granite		
25	Hungry Grove Granite		
26	Koskaecodde Pluton		
27	Middle Ridge Granite	109	2.33
28	Third Berry Pond Granite	4	0.09
29	Sall the Maid Granite		
30	Gull Lake Intrusive Suite		
31	Devils Room Granite		
32	Laughlins Hill Gabbro		
33	Seal Cove Gabbro		
34	Anchor Drogue Granodiorite		
35	Cape Roger Mountain Batholith	18	0.39
36	Swift Current Granite	61	1.31
37	Berry Hills Granite	5	0.11
38	St. Lawrence Granite	189	4.05
39	Grole Diorite		
40	Furbys Cove Granite		
41	Harbour Breton Granite	33	0.71
42	Pass Island Granite	15	0.32
43	Belleoram Granite	14	0.30
44	Cross Hills Complex	111	2.38
45	Holyrood Granite	79	1.69
46	Rencontre Lake Granite		
47	Sage Pond Granite		
48	Francois Granite	180	3.85
49	Chetwynd Granite	48	1.03
50	Otter Point Granite		
51	Roti Granite East		
52	Hawkes Nest Pond Porphyry		
53	Petites Granite		
54	Strawberry Granite		
55	Windowglass Hill Granite		
56	Rose Blanche Granite	12	0.26
57	Ironbound Monzonite	34	0.73
58	Peter Snout Granite		
59	Cochrane Pond Granite	5	0.11
60	Buck Lake Granite		
61	Baggs Hill Granite		
62	Rotten Brook Granodiorite	10	0.21
63	Roti Granite West	16	0.34
64	Nitty Gritty Brook Granite		
65	Isle aux Morts Brook Granite		
66	Mollyguajeck Pluton		
67	Aspen Brook Pluton	9	0.19
68	Barren Lake Gabbro		
69	Belle Island Granite		
70	Big Round Pond Granite		
71	Brighton Gabbro		
72	Burlington Granodiorite		
73	Business Cove Granite		
74	Cape Brule Porphyry		
75	Cape Freels Granite	31	0.66
76	Cape Ray Granite		
77	Causeway Diorite		
78	Cinq Cerf Complex		
79	Clarenville Granite	8	0.17
80	Coaker Porphyry		
81	Colchester Granodiorite		
82	Cripple Back Lake Quartzdiorite		
83	Deadmans Bay Granite	83	1.78
84	Dolland Arm Head Quartzdiorite		
85	Dolland Quartzdiorite		
86	Dover Fault Granite		
87	Dunamagon Granite		
88	Ernie Pond Gabbro		
89	Feeder Granodiorite		
90	Fogo Diorite – Gabbro Complex		
91	Fogo Granite		
92	Fogo Island Batholith		
93	Fredrickton Pluton	21	0.45
94	Gander Lake Pluton	19	0.41
95	Goose Hill Granite		
96	Grapnel Gabbro		
97	Gull Pond Granite		
98	Hare Hill Granite		
99	McCallum Granite	66	1.41
100	Harpoon Hill Gabbro		
101	Hodges Hill Granite		
102	Hungry Hill Gabbro		
103	Hungry Mtn Complex		
104	Indian Head Complex		
105	Indian Point Complex		
106	Iona Islands Intrusion		
107	Island Pond Pluton		
108	La Poile Batholith		
109	LaScie Granite		
110	LaScie Igneous Suite		
112	Lloyds River Intrusive Suite		
113	Lockers Bay Granite		
114	Loon Bay Granite		
115	Louil Hills Granite		
116	Maccles Lake Granite	27	0.58
117	Mansfield Head Granodiorite		
118	Middle Brook Granite	47	1.01
119	Moose Lake Granite		
120	Mt. Margaret Gabbro		
121	Mt. Peyton Intrusive Suite	64	1.37
122	Newport Granite	19	0.41
123	North Pond Granite		
124	Northern Granite		
125	Overflow Pond Granite	9	0.19
125	Overflow Pond Granite		
126	Partridge Point Granite		
127	Port aux Basques Granite		
128	Powder Horn Diorite Complex		
129	Puncheon Diorite		
130	Ragged Harbour Pluton	11	0.24

Table 1. *(continued)*

Pluton Number	Name of Unit or Plutonic Suite	Valid Records	Percent of Data
131	Red Island Granite	11	0.24
132	Red Rocks Granite		
133	Reddits Cove Gabbro		
134	Rocky Bay Pluton	8	0.17
135	Rodeross Lake Troctolite		
136	Seal Island Bight Syenite		
137	Seal Nest Cove Tonolite		
138	Skull Hill Granite		
139	South Lake Igneous Complex		
140	South Pond Granite		
141	South Pond Pluton		
142	Southwest Brook Intrusive Suite		
143	Tacks Beach Pluton		
144	Forche Harbour Pluton	11	0.24
145	Terra Nova Granite	24	0.51
146	Terra Nova River Pluton	6	0.13
147	Terra Nova River West	4	0.09
148	Cat Arm Granite		
149	Tilting Igneous Complex		
150	Topsails Granite		
151	Topsails Intrusive Suite		
152	Tulks Hill Granite		
153	Tulks Pond Syenite		
154	Twillingate Granite	55	1.18
155	Twin Lakes Diorite Complex		
156	Valentine Lake Quartz Monzonite		
157	Wadsworth Gabbro		
158	Wareham Granite		
159	Wellmans Cove Diorite		
160	Coney Head Complex		
161	Whaleback Gabbro		
162	White Point Pluton		
164	Kings Point Complex		
165	Wild Cove Pond Igneous Suite		
166	Winterland Porphyry		
167	Cloud River Pluton		
168	Hooping Harbour Pluton		
169	Hooping Harbour Pluton II		
170	Horse Chops Pluton		
171	Lake Michel Pluton		
172	Leg Pond Pluton		
173	Budgell Harbour Gabbro		
174	Great Burnt Lake Granite	53	1.13
175	North Bay Granite (part)	21	0.45
176	Unassigned		
177	Steel Pond Gabbro	38	0.81
178	Ebbegunbaeg Granite	22	0.47
179	Georges Pond Granite		
180	Potato Hill Diorite		
181	Taylor Brook Gabbro Complex		
182	North Branch Brook Granite		
183	Killdevil Hill Granodiorite		
184	Lomond River Granodiorite		
185	Deadwolf Brook Granite		
186	Unassigned		
187	Unassigned		
188	Main Gut Gabbro		
189	Boogie Lake Monzonite		
190	Top Pond Brook Tonalite		
191	Costigan Lake Intrusion		
192	Tower Hill Intrusion		
193	Dawes Pond Pluton		
194	Salmon Pond Granite		
195	Mansfield Cove Complex		
196	Hall Hill Complex		
197	Loon Pond Pluton		
198	Main River Granite		
199	Lemottes Lake Granite		
200	Spread Eagle Gabbro		
202	Deepwater Point Granodiorite	5	0.11
202	Gander Lake West Pluton	3	0.06
-	No Pluton Number Assigned	203	4.35
	TOTAL NUMBER OF RECORDS	4670	100.00

NOTES: 1. As the database is presently being checked, many of these figures are subject to revisions.
2. Some 'plutons' are actually subdivisions of others within the database. For example, 'Hungry Grove Granite' (25) is a unit within the Ackley Granite Suite (15)
3. 'Plutons' with large amounts of data (e.g., Burgeo Intrusive Suite) are composite, and can be extensively subdivided.

A number of simple numerical tests will be performed. For major-element data, checking calculated totals will catch most data entry errors. Trace-element data errors are far more difficult to detect. The simplest and most effective procedure for detection is to examine element-frequency patterns for groups of 'outliers' that have extremely high or low concentrations, particularly where such values are inconsistent with major-element indices (e.g., SiO_2 content) or outside the normal range for granitoid rocks. Outlying trace-element values (notably for U, Mo, Cu, Pb, Zn, etc.) will also highlight mineralized samples that are not presently identified as such.

CHANGES TO DATABASE FORMAT AND ORGANIZATION

Developing a database of this size and complexity is an evolving process, as it is impossible to foresee all problems at the outset. A number of format modifications and additions are currently being considered.

There is a need for a method of identifying both the original source of samples (i.e., project, year, geologist), and the sources and analytical methods for geochemical data, as data for a single 'pluton' may come from a variety of sources. It is not good practice to compare trace-element data derived by different methods at different laboratories, particularly if precision and accuracy data are unavailable; the re-analysis program (see below) is the long-term solution to this problem. At present, using a series of numerical codes to cover all of the various analytical combinations seems to be the best solution, although it is unavoidably cumbersome. An alternative solution, which involves the creation of a series of variables such as Ba(XRF), Ba(AA), Ba(ICP) etc., would result in a huge increase in the size of the database, and consequent data-processing problems.

There is also a requirement for a consistent method for denoting subunit or map unit that will result in a unique value for each subunit of each 'pluton' to be labelled in the file description. Using existing map units is impractical, as their format varies so greatly (e.g., 10, 10a, 10.3, Dg, Og2, SDgp, etc.) and they are non-unique. The best option appears to be a decimal format where the integer portion is the 'pluton number', e.g., 10.01, 10.02, 10.03, 10.04 etc.

As Newfoundland incorporates portions of UTM zones 21 and 22, there may also be a need to add extra coordinate variables that provide a consistent framework for plotting, by recalculating to a single UTM zone. At the present time, data are converted to zone 21 coordinates by an in-house program prior to plotting, but it cannot be assumed that all end-users will be able to do this. If this approach is adopted, the original coordinates will also need to be retained, as these are essential in dealing with existing topographic maps. Alterations to database formats within SPSS-X are not difficult, but the 'nuisance factor' increases with the size of the file involved. It is therefore advisable to address such considerations, and minor matters such as revisions of variable names, before adding any newly acquired or assembled data.

RE-ANALYSIS OF OLDER SAMPLE POPULATIONS

As previously stated, there is considerable variation in the vintage and quality of geochemical data. An area of particular concern is the Strong *et al.* (1974) data, which are an important source of information.

REPRODUCIBILITY CHECK OF STRONG *ET AL.* (1974) DATA

In order to assess the reproducibility of the Strong *et al.* (1974) data, 50 sample powders were selected on a random basis, and re-analyzed via the NDME laboratory. Results suggested that some of the major-element and trace-element data may not be completely reliable. Some examples are illustrated in Figure 3; these cover a range from good reproducibility (e.g., Zr) to serious inconsistency (e.g., MgO).

On the basis of this investigation, it was decided to re-analyse the entire Strong *et al.* (1974) sample collection for nearly all the elements. This should eliminate reliability problems, and ensures that data are of comparable quality to more recent surveys. In addition, it provides a wide range of trace-element data (e.g., Li, Be, Ga, Y, Nb, Mo, La, Ce) that were not determined during the original survey.

WORK IN PROGRESS

Re-analysis of the Strong *et al.* (1974) data was mostly completed by December, 1990, with the exception of a small number of samples (< 5 percent), for there are insufficient quantities of the original powder. Data have been keypunched via NLCS, and await a series of integrity checks. Updating will not take place until location and identification problems with the existing database are eliminated (see above). If missing samples cannot be located in any form, their records will probably be eliminated.

It is anticipated that complete re-analysis will also be required for other sample populations of similar vintage. One obvious example is the DeGrace *et al.* (1976) survey of the eastern Baie Verte Peninsula, for which original sample powders are proving difficult to locate. It is intended that similar reproducibility checks be made on data from the late 1970's.

Although the trace-element suite determined since about 1980 is fairly consistent, there are some variations between workers, notably with regard to elements such as Be, Li and Cd, and external analyses of Sn and W. Ideally, these inconsistencies should be resolved by selective re-analysis of samples affected, but this will depend upon available resources. This applies particularly to Sn and W, which are external analyses, and may be better approached by analyzing sample subsets. In the case of W, widespread use of tungsten carbide pulverization tools prior to 1980 renders re-analysis for this element futile in many areas, unless unpowdered sample splits are available.

FIELD WORK DURING 1989 AND 1990 FIELD SEASONS

Very little field work has been conducted to date as part of this project. In 1989, approximately 1 month of field work was conducted to familiarize the senior author with the characteristics and settings of Newfoundland granites, and to provide a starting point for a subcollection of representative and reference samples for isotopic analysis and other work (see below). In 1990, some low-cost field work was accomplished in the Placentia Bay region of the Avalon Peninsula, with emphasis on probable Paleozoic intrusions. These are of interest, as they afford a chance to verify the presence or absence of older basement rocks beneath the Avalon Zone via Nd isotopic analysis. Several of these intrusions are also unrepresented or poorly represented in the present granitoid database.

FUTURE DIRECTIONS

In this final section, a number of future objectives and directions for this project are discussed briefly. It should be emphasized that this is by no means an exhaustive list, and that any additional ideas or proposals for work not specifically mentioned below are welcome. Some of the work discussed below is dependent upon the participation of interested outside researchers.

BUILDING A TRULY REPRESENTATIVE DATABASE

Although the present core of the database contains an impressive amount of geochemical information, it is far from representative (Figure 2). This problem has two aspects. First, the many plutonic suites that are not represented in the

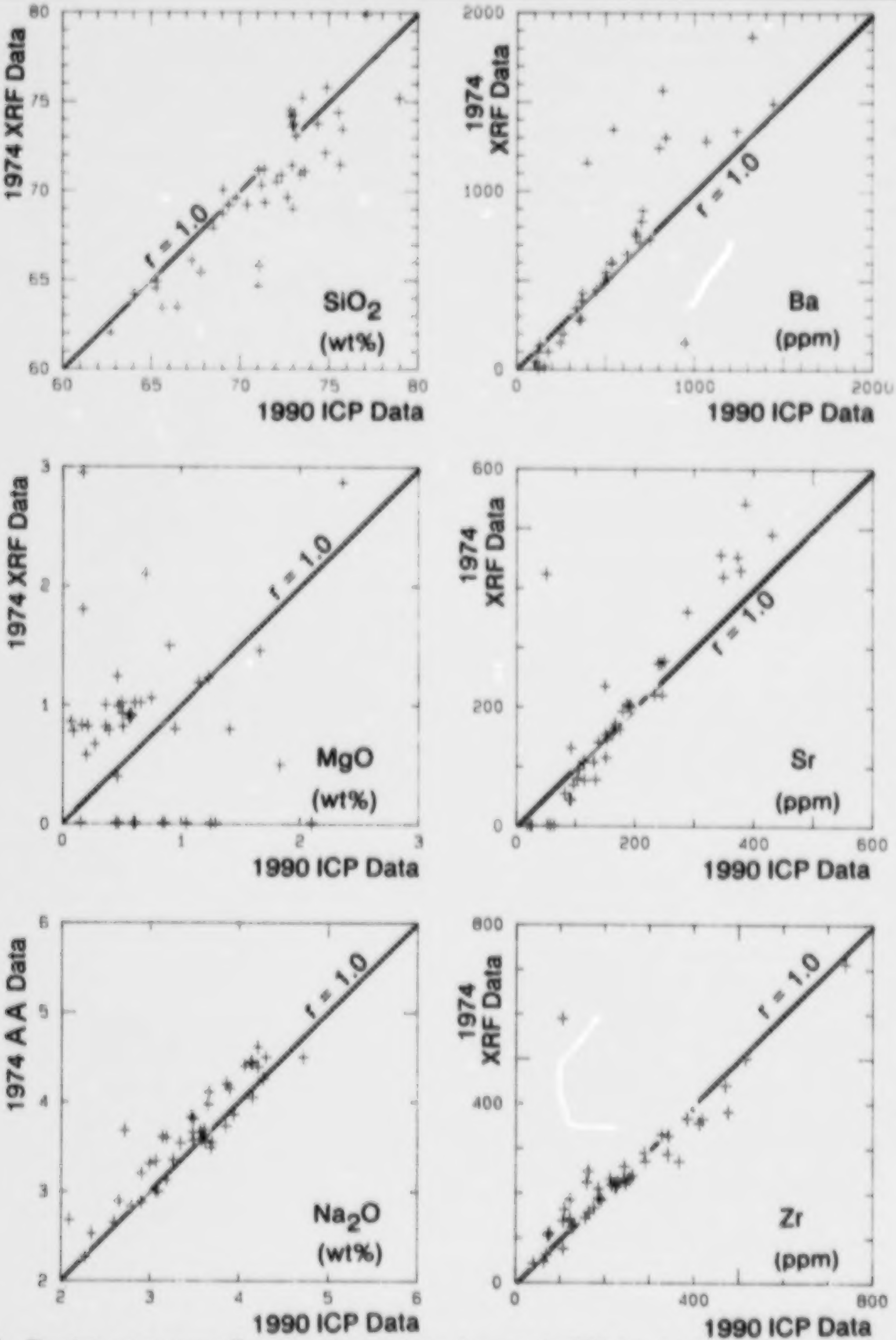

Figure 3. *Bivariate scattergrams illustrating the correlation between the XRF data for SiO_2, MgO, Na_2O, Ba, Sr and Zr of Strong et al. (1974) and ICP data acquired in 1990 as part of a reliability test based on 50 randomly selected powders from the original survey. The diagonal line (r=1.0) illustrates the relationship expected for perfect correlation of both sets of analyses.*

database need to be examined and sampled. Second, the coverage of many areas surveyed by previous studies requires upgrading.

There are advantages to having a numerical database that is truly representative, i.e., in which plutonic suites and rock types are represented in approximate proportion to their areal abundance. First, measures of central tendencies such as means and medians are not distorted in favour of specific areas. Second, and perhaps more importantly, extensive parameters such as frequency histograms and proportions of different rock types can be used as descriptive and comparative tools, in addition to conventional intensive parameters such as mean elemental concentrations.

Granitoid rocks of the south coast of Newfoundland are represented at an average density of 1 sample per 4 km^2 or better. Although it is anticipated that granites in some areas of proposed AMD 1990-1995 regional mapping projects (e.g., the Mount Peyton area) will be sampled on a comparable scale, it is unrealistic to expect that coverage can be brought to this level in all areas. However, it is hoped that field work in years to come, as part of this and other AMD 1990-1995 projects, will allow coverage of much of the island at densities of between 1 sample per 16 and 1 sample per 25 km^2. Although the database (on an island-wide scale) will still be unrepresentative, it will be simple to produce a representative version for interpretative purposes by selecting random subsets from densely sampled areas at a selection level of 20 to 25 percent. Alternatively, subsets could be selected on a purely geographic basis. In localized studies in such areas, the full complement of samples can be retained.

RELEASE OF GEOCHEMICAL DATA IN DIGITAL FORMAT

This is, of course, one of the prime objectives of this project. It is intended to release accumulated geochemical data in digital format, progressively between 1991 and 1993, commencing with data from eastern and parts of southern Newfoundland, where much of the present database is localized (Figure 2). Data releases will include existing high-quality geochemical data, re-analysed data from early surveys, and data from mapping and sampling under the auspices of this project. Each release will be accompanied by printed documentation that summarizes the geology, petrology, geochemistry and economic potential of the plutonic suite(s), based on previous mapping and new field work.

EXPANSION OF THE GEOCHEMICAL DATABASE

In addition to expanding the number of records, to provide more representative coverage, attempts will be made to broaden the spectrum of elements for which data are available. Recent Departmental projects incorporate a wide trace-element suite, but some elements are beyond present analytical capabilities. These include Au, As, Sb, W, Sn (ore elements or indicators of such) and Hf, Ta, Cs, Yb and Sc (important in classification and petrogenetic modelling). From a petrogenetic and economic viewpoint, full rare-earth element (REE) analyses are also a valuable asset. The ICP mass-spectrometer at Memorial University is capable of providing a significant portion of this data, but external analysis by NAA or XRF will be needed for some elements.

It is clearly unrealistic to expect that data for all these elements can be obtained for the entire database, but it is intended to analyze a representative subset from most plutonic suites.

MINERALOGICAL AND MINERAL GEOCHEMISTRY STUDIES

This aspect remains virtually untouched in Newfoundland, but is of interest for several reasons. First, variations in mineral chemistry within individual plutons may be valuable pathfinders for mineralizing systems. For example, systematic changes in biotite, chlorite and muscovite compositions are effective in discrimination of mineralized and barren areas of the Ackley Granite Suite (Tuach, 1987).

Second, on a regional scale, mineralogical studies can provide information about a number of physico-chemical factors such as source components, depths of emplacement, volatile contents, oxygen fugacities and liquidus temperatures—areas that are largely unknown quantities for most Newfoundland intrusions, except in the most general sense. In this context, the work of Ague and Brimhall (1988a, b) on biotite compositions in the Sierra Nevada batholith is of particular relevance, and a similar study could easily be initiated in Newfoundland.

Third, mineral geochemistry is a valuable adjunct to classification schemes based upon petrology and whole-rock geochemistry. In strongly porphyritic granitoid rocks that are probably 'cumulates' (in a very broad sense), mineral geochemistry trends are far better indicators of differentiation trends than whole-rock compositions, which are strongly influenced by retention of phenocrysts and sample size.

Work of this type that can be accomplished by electron microprobe techniques is fairly straightforward; however, at the present time, such methods are not capable of providing trace-element data that are better than semi-quantitative. Conducting mineral separations is extremely time-consuming and labour-intensive, and thus expensive. Work of this type can probably only be practically accomplished via a thesis or similar research contract project.

INTEGRATION OF LITHOGEOCHEMICAL AND OTHER REGIONAL DATABASES

Since the mid-1980's, a growing emphasis has been placed at NDME toward development of computer databases for a range of spatial data, including surficial geochemistry (e.g., lake and stream sediments) and geophysical information. This has been coupled with acquisition of technology that permits integrated display and analysis via image-analysis and geographic information systems.

Integration of lithogeochemical and surficial geochemical information is a direction of considerable promise, as regional multi-element lake-sediment data have considerable utility in mapping bedrock characteristics (e.g., Davenport, 1982; Kerr and Davenport, *in press*). The availability of lithogeochemical data at a similar (or closer) spacing should allow the definition of surficial signatures for specific plutonic associations, and aid in developing geological maps for poorly-exposed areas. Similar arguments apply to integration of geochemical and geophysical data.

ISOTOPIC GEOCHEMISTRY

In 1988, a project to investigate the isotopic systematics of Newfoundland granites was established, with funding from LITHOPROBE supporting science grants to workers at Memorial University. The objectives are to establish the probable source material(s) for individual plutonic suites, and to identify the nature and extent of various lower crustal blocks beneath the Newfoundland Appalachians. Obviously, this type of information is also important in assessing the significance of various plutonic suites with reference to the Appalachian tectonic cycle.

Samples archived from previous NDME mapping projects (and external sources) were analyzed in 1988 and 1989 for Nd and oxygen isotopic compositions. These preliminary results are discussed by Fryer *et al.*, (1989) and Kerr *et al.*, (1990b), and have a number of important implications for crustal structure beneath Newfoundland. Numerous additional samples were collected for isotopic investigation during the 1989 and 1990 field seasons. These are presently being processed through chemical separations to collect Nd for mass-spectrometry, and results should be available during 1991. Further sampling for isotopic analysis will be conducted in conjunction with field work in 1991 and 1992.

In addition to Nd and oxygen, a number of other isotopic systems are of potentially great importance in assessing the origins of these magmas. Initial Sr isotopic ratios are already available from many intrusions via Rb−Sr isochron studies. However, U−Pb geochronology has shown that many Rb−Sr ages are erroneously young, suggesting isotopic disturbance, and initial ratios from such sources may not be reliable. An alternative approach may be to use mineral separates for Sr analysis−Sr-rich, Rb-poor species such as apatite may be insensitive to processes that affect whole-rock Sr-isotope systematics. Clinopyroxene might also be a possible candidate in some plutonic suites of more mafic composition.

Hafnium isotopic compositions have to date been utilized only by a very small number of studies utilizing granitoid rocks (e.g., Patchett *et al.*, 1981), but have found wider application in studies of mantle evolution. The Lu−Hf system is similar in principle to the more widely used Sm−Nd system and provides similar evidence regarding crustal residence periods, but with greater sensitivity. The best materials for initial Hf isotopic analysis are widely acknowledged to be zircon separates, as these contain abundant Hf, but no Lu. Uranium−lead geochronology over the last few years has created a substantial inventory of zircon separates, and the idea of obtaining regional Hf isotope data from this material should be investigated. Common Pb isotope data, normally obtained on K-feldspar separates, may also be a valuable source of information relating to source terranes.

GEOCHRONOLOGICAL STUDIES

Geochronological control is of great importance in any attempt to group Newfoundland granitoid suites by association or setting, and precise age determinations are important in interpreting isotopic signatures in terms of petrogenesis and source(s). Since 1980, the focus of geochronology programs has been on U−Pb zircon techniques, mostly via the Royal Ontario Museum laboratory. A large number of granitoid plutons have been dated by T.E. Krogh, G.R. Dunning and coworkers, and the stratigraphic framework for Appalachian plutonism has become much clearer as a result. As part of this project, U−Pb ages were obtained by R.D. Tucker in 1989 from the Middle Ridge Granite, the Cape Freels Granite and the François Granite. Both the Cape Freels and Middle Ridge granites have given Silurian ages, adding to the large body of data suggesting an important period of Silurian magmatic activity in Newfoundland (Dunning *et al.*, 1988). The François Granite has been shown, not surprisingly, to be of Middle Devonian age. It is anticipated that U−Pb dating of granitoid plutons will continue to be conducted as part of regional mapping programs under AMD 1990-1995 as they are commonly important in establishing regional age relationships. It is also hoped that this granitoid database project will also be able to fund small amounts of geochronological work directly over the next few years.

Although the conventional U−Pb zircon technique commonly used in North America provides precise ages of emplacement for many granitic rocks, it is less effective in identifying and unravelling complex inherited components that may yield valuable information regarding potential source material(s) for magmas. The Sensitive High-Resolution Ion MicroProbe (SHRIMP) developed in Australia can analyze single grains and even portions of grains (e.g., growth zones and inclusions) *in situ*. Recent work by I.S. Williams and others in Australia (personal communications, 1990), illustrates the great potential of this instrument to resolve some long-standing problems in granite petrology.

In summary, there is no doubt that ion microprobe studies would make an extremely valuable contribution to a project concerned partly with the origins of granitoid magmas. As a long-term objective, this idea should definitely be further explored, as the SHRIMP technology will have an increasingly important role in years to come, and is ideally suited to the types of problems that granitoid rocks present.

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REFERENCES

Ague, J.J. and Brimhall, G.H.
1988a: Regional variations in bulk chemistry, mineralogy, and the compositions of mafic and accessory minerals in the batholiths of California. Geological Society of America Bulletin, Volume 100, pages 891-911.

1988b: Magmatic arc asymmetry and distribution of anomalous plutonic belts in the batholiths of California: Effects of assimilation, crustal thickness, and depth of crystallization. Geological Society of America Bulletin, Volume 100, pages 912-927.

Blackwood, R.F.
1983: Notes on the geology of the Great Gull Lake map area (2D/6), Newfoundland; to accompany map 82-71. Newfoundland Department of Mines and Energy, Mineral Development Division, 10 pages.

Butler, J.
1988: Datafile management. *In* Report of Activities for 1988. Newfoundland Department of Mines and Energy, Mineral Development Division, page 93.

Chorlton, L.
1980: Geology of the La Poile River area (110/16), Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 80-3, 85 pages.

Colman-Sadd, S.P., Dickson, W.L., Elias, P. and Davenport, P.H.
1981: Rock geochemical data from plutonic intrusions of south-central Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File NFLD (1157).

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. (Compilers)
1990: Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-01.

Colman-Sadd, S.P. and Swinden, H.S.
1982: Geology and mineral potential of south-central Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-8, 102 pages.

Coyle, M.
1989: Geology of the Springdale Group: a newly-recognized Silurian epicontinental type Caldera in Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland.

Davenport, P.H.
1978: Uranium distribution in the granitoid rocks of eastern Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Open file NFLD (946), 143 pages.

1982: The identification of mineralized granitoid plutons from ore element distribution patterns in regional lake sediment geochemical data. Canadian Institute of Mining and Metallurgy Bulletin, pages 1-12.

DeGrace, J.R., Kean, B.F., Hsu, E. and Green, T.
1976: Geology of the Nippers Harbour map area, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 76-3, 73 pages.

Dickson, W.L.
1974: The general geology and geochemistry of the granitoid rocks of the northern Gander Lake Belt, Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, 164 pages.

1983: Geology, geochemistry and mineral potential of the Ackley granite and parts of the Northwest Brook and Eastern Meelpaeg Complexes southeast Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 83-6, 129 pages.

Dickson, W.L., Kerr, A., Hayes, J.P. and Fryer, B.J.
1990: Geochemistry of late- to post-orogenic granitoid plutons across the Newfoundland Appalachians: Relationship to tectonic zones. Geological Association of Canada, Annual Meeting, Vancouver, May 1990, Program with Abstracts, page A32.

Dickson, W.L., O'Brien, S.J. and Hayes, J.P.
1989: Aspects of the mid-Paleozoic magmatic history of the south-central Hermitage flexure area, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 81-95.

Dunning, G.R., Krogh, T.E., O'Brien, S.J., Colman-Sadd, S. and O'Neill, P.
1988: Geochronologic framework for the Central Mobile Belt in southern Newfoundland, and the importance of Silurian Orogeny. Joint Annual Meeting, Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists, St. John's, May 1988, Program with abstracts, page A34.

Elias, P.
1979: Granite geochemistry project, Bay d'Espoir area. *In* Report of Activities for 1979. Newfoundland Department of Mines and Energy, Mineral Development Division, pages 35-37.

1980: Granite geochemistry project, Bay d'Espoir area. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 80-1, pages 50-52.

1982: Geochemistry and petrology of granitoid rocks of the Gander Zone, Baie d'Espoir area, Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, 271 pages.

Fryer, B.J. (Compiler)
1989: The isotopic and LILE compositions of granitoid rocks as clues to deep crustal structure in LITHOPROBE EAST. Lithoprobe East Transect Meeting Report, October 1989, Department of Earth Sciences, Memorial University of Newfoundland, pages 37-40.

Furey, D.
In preparation: Belleoram and Harbour Breton Granites, southeast Newfoundland. Ph.D. thesis, Memorial University of Newfoundland.

Hayes, J.P.
In preparation: Regional setting and genesis of the Eastern Avalon high-alumina belt. M.Sc. Thesis, Memorial University of Newfoundland.

Hayes, J.P., Dickson, W.L. and Tuach, J.
1987: Newfoundland granitoid rocks. Map with marginal notes. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 87-85.

Hibbard, J.P.
1983a: Geology of the Island of Newfoundland (preliminary version). Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 83-106.

1983b: Geology of the Baie Verte Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Memoir 2, 279 pages.

Jayasinghe, N.
1978: A petrological, geochemical and structural study of the Wesleyville area, Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, 350 pages.

Kerr, A.
1989: Integration and interpretation of geochemical data from granitoid rocks of insular Newfoundland: Preliminary work during the 1989 field season. *In* Report of Activities for 1989. Newfoundland Department of Mines and Energy, Mineral Development Division, pages 39-40.

1990: Integration and interpretation of geochemical data from granitoid rocks of insular Newfoundland: Activities for 1990. *In* Report of Activities for 1990. Newfoundland Department of Mines and Energy, Geological Survey Branch, pages 36-39.

Kerr, A. and Davenport, P.H.
In press: Application of geochemical mapping techniques to a complex Precambrian shield area in Labrador, Canada. Journal of Geochemical Exploration.

Kerr, A., Dickson, W.L., Hayes, J.P. and Fryer, B.J.
1990a: Geochemical overview of late- and post-orogenic granites across Newfoundland: Part of a long-term project to integrate and interpret our large inventory of data. Lithoprobe East Transect Meeting Report, October, 1990, Memorial University of Newfoundland, pages 117-135.

Kerr, A., Fryer, B.J. and Jenner, G.A.
1990b: Contrasts in the elemental and isotopic signatures of granitoid suites that intrude major crustal boundaries in eastern Canada. Seventh International Conference on Geochronology and Isotope Geology, Canberra, Australia, 1990, Abstracts, page 55.

Miller, R.R.
1990: Rare-metal potential in insular Newfoundland. *In* Report of Activities for 1990. Newfoundland Department of Mines and Energy, Geological Survey Branch, pages 82-86.

O'Brien, S.J., Dickson, W.L. and Blackwood, R.F.
1986: Geology of the central portion of the Hermitage Flexure Area, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 189-209.

Owen, J.V.
1988: Geology of the Long Range Inlier, Newfoundland. Unpublished report, (DSS contract 23233-7-0007/01-SZ).

Patchett, P.J., Kouvo, O., Hedge, C.E. and Tatsumoto, M.
1981: Evolution of continental crust and mantle heterogeneity: Evidence from Hf isotopes. Contributions to Mineralogy and Petrology, Volume 78, pages 279-297.

Poole, J.
In preparation: The François Granite, south coast of Newfoundland. M.Sc. thesis, Memorial University of Newfoundland.

Strong, D.F., Dickson, W.L., O'Driscoll, C.F. and Kean, B.F.
1974: Geochemistry of eastern Newfoundland granitoid rocks. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 74-3, 140 pages.

Teng, H.C.
1974: A lithogeochemical study of the St. Lawrence granite, Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, 194 pages.

Tuach, J.
1987: The Ackley high-silica magmatic/metallogenic system and associated post-tectonic granites, southeast Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, 455 pages.

Whalen, J.B. and Currie, K.L.
1983: The Topsails igneous terrane, western Newfoundland. 1:100,000 map and marginal notes. Geological Survey of Canada, Open File 923.

Whalen, J.B., Currie, K.L. and Chappell, B.W.
1987: A-type granites: descriptive and geochemical data. Geological Survey of Canada, Open File 1411, 33 pages.

Williams, H.
1967: Geology, Island of Newfoundland. Geological Survey of Canada, Map 1227A.

Williams, H., Dickson, W.L., Currie, K.L., Hayes, J.P. and Tuach, J.
1989: Preliminary report on classification of Newfoundland granitic rocks and their relations to tectonostratigraphic zones and lower crustal blocks. *In* Current Research. Geological Survey of Canada, Paper 89-1B, pages 47-53.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 141-[illegible]

DEFORMED LOWER PALEOZOIC PLATFORM CARBONATES, GOOSE ARM–OLD MAN'S POND

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ABSTRACT

The Goose Arm–Old Man's Pond area embraces a sinuous terrane of polydeformed lower Paleozoic miogeoclinal rocks that lies between the Humber Arm and Old Man's Pond allochthons. Preliminary studies indicate the area possesses comparable lithostratigraphy, biostratigraphy and structural geology to other parautochthonous terranes of the Great Northern Peninsula. In particular, thrusts have juxtaposed distal shelf-facies, upon more proximal shallow shelf-facies.

Cambrian rocks in the section at Goose Arm include siliciclastic and carbonate rocks. At the base of the section, mixed siliciclastic and lesser carbonate strata of the Penguin Cove Formation are correlated with the Hawke Bay Formation (Bridge Cove Member) of Canada Bay. Trilobites from low in the formation indicate a possible Albertella Zone *age. The overlying Port au Port Group consists of limestone and dolostone. Thick oölitic and oncolitic limestone of the March Point Formation contain trilobites correlative with the late Middle Cambrian* Olenoides longispinus *and* Ehmaniella cloudensis *zones of Canada Bay; these are succeeded by cyclic, peritidal dolostone, argillaceous dolostone and limestone of the Petit Jardin Formation. Previously unrecorded* Cedaria *and* Crepicephalus *zone trilobite faunas from the Petit Jardin Formation indicate that most of it was deposited during the early Late Cambrian Dresbachian Stage. Peritidal dolostones dominate the Berry Head Formation but it also includes a massive basal sequence of cryptalgal mounds and an upper member of interbedded limestone and dolostone. The latter includes previously unknown trilobite faunas correlative with the* Saukia, Mississquoia *and* Symphysurina *zones, suggesting that the Cambrian–Ordovician boundary occurs in the upper 45 m of the formation.*

Ribbon limestone, phyllite and limestone conglomerate mark the allochthonous Reluctant Head Formation and are overlain by unnamed dolostones and the Berry Head Formation in the Reluctant Head Thrust. Trilobites from the top of the Reluctant Head Formation indicate a correlation with the lower part of the Petit Jardin Formation. This suggests that the shelf evolved through the Middle and early Late Cambrian as a prograding ramp, and was transformed to a platform in the latest Cambrian.

The miogeoclinal rocks are assembled in a number of thrusts that were transported westward and later deformed by northeast-trending folds. At lower structural levels, the folds are steepened to recumbent to the west. This is in contrast to folds in higher structural slices that are for the most part east-verging, associated with west-dipping cleavage and recumbent near the Old Man's Pond Allochthon. Polyphase deformation of the carbonates occurred during westward thrusting. It is marked by small-scale structures that include penetrative cleavage (transposed bedding), bedding co-planar foliation in limestone marbles, boudinaged dolostone interbeds, and recumbent folds that are refolded, locally into sheath folds. However, there are some large-scale, west-verging, recumbent folds in thrust footwalls. The main thrusts in the area are the Reluctant Head and Penguin Head thrusts. Others also occur and are locally linked to shear zones.

INTRODUCTION

Carbonate rocks of the Goose Arm–Old Man's Pond area, although mapped and described in several studies, have remained relatively poorly understood within the regional geological framework of western Newfoundland. Detailed lithobiostratigraphic studies and preliminary geological mapping in the area began in the summer of 1990. The highlights of this work indicate that the area contains rock sequences that fundamentally affect the geological picture of western Newfoundland during the lower Paleozoic. The highlights include:

a) the carbonates are probably allochthonous,

b) they are polyphased deformed in a number of thrust slices,

c) Middle to Upper Cambrian siliciclastics and carbonates were deposited upon a prograding ramp shelf,

d) common, low diversity trilobite faunas provide reasonably accurate biostratigraphic correlation, and

e) the faunas locate the Cambrian–Ordovician boundary within 45 metres.

Although the area is mentioned by Schuchert and Dunbar (1934), it was largely ignored until the 1950's when Brinex Limited began exploration in the area. A thesis study and subsequent work by Lilly (1961, 1963) in conjunction with one by McKillop (1963) near Corner Brook, provided the first subdivision of the rocks. Lilly (1961) subdivided the sequence at Goose Arm into the Penguin Cove, Hughes Brook and Corner Brook formations. Near Old Man's Pond, Lilly (1961) identified the Reluctant Head Formation, which he assigned to the Upper Cambrian. More recent studies were those of Levesque (1977) and Chow (1986). They subdivided the succession and placed it within its western Newfoundland context. However, because of the general lack of fossil control, correlations remained largely speculative. Structural study of the Old Man's Pond Allochthon (Gillespie, 1983) provided some description of the rocks of the Reluctant Head Formation. Later base-metal exploration (Wilkinson, 1983) relied heavily upon structural and stratigraphic mapping that showed a number of thrust slices occur in the Goose Arm area.

GEOLOGICAL SETTING

Lower Paleozoic miogeoclinal and foreland basin rocks, which are mainly carbonates, occupy a sinuous belt between the Humber Arm Allochthon in the west and the Old Man's Pond Allochthon in the east (Figure 1). Early Cambrian to Early Ordovician passive margin sedimentary sequences were succeeded by a Middle Ordovician carbonate to flysch sequence. This was deposited in a foredeep above the collapsed margin during initiation of Taconic orogenesis.

The miogeocline, unlike its counterpart throughout much of the Northern Peninsula, is folded and faulted. However, the lithostratigraphy is closely comparable with that of the parautochthonous thrust belt of Canada Bay to Pistolet Bay (Knight, 1986, 1987). This suggests that the exposed miogeocline in the area is indeed parautochthonous, as previously advocated by Waldron (1988) and Cowan and James (1989). The first deformation of the miogeocline accompanied westerly emplacement of the Taconic allochthons including westward-directed thrusting (Waldron, 1988). The area was then affected by Acadian deformation in the Late Silurian to Early Devonian (Cawood and Williams, 1988). Eastward-directed back thrusting placed the miogeocline over the Old Man's Pond Allochthon, although Waldron (1988) interprets the allochthon to be a structural window beneath tectonically duplicated carbonates.

STRATIGRAPHY

The autochthonous succession in the Goose arm area comprises units of the Labrador, Port au Port, St. George and Table Head groups. Taconic flysch of the Goose Tickle Group is preserved in the area but is largely dismembered as part of a unit of strongly deformed melange. Strata within the Reluctant Head Thrust do not conform to the standard Cambrian subdivisions of the platform but include the lithologically distinct Reluctant Head Formation, which is the time equivalent of the lower part of the Port au Port Group. It will remain outside the group structure. Only the Cambrian stratigraphy has been logged in any detail (Figure 2).

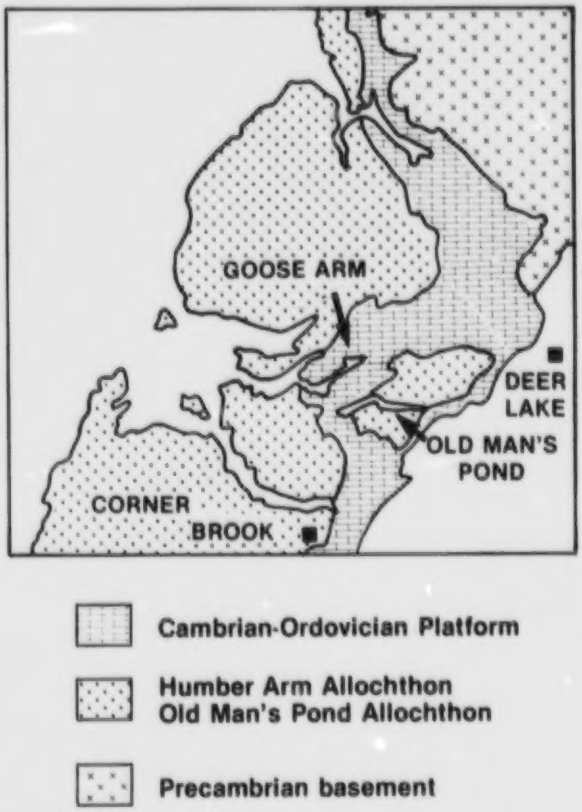

Figure 1. *Location map of the Goose Arm–Old Man's Pond study area showing the main geological terrains.*

PENGUIN COVE FORMATION, LABRADOR GROUP

The Penguin Cove Formation occupies the core of the Goose Arm Anticline. It comprises a mixed siliciclastic–carbonate succession of shallow subtidal to possibly intertidal origin. The succession consists of a lower member, 108 m thick, of intercalated siliciclastics and metre-thick oncolitic limestone units. This is separated by a covered interval that possibly obscures 110 m of strata from an upper member, 87 m thick, comprising mostly siliciclastic rocks. The latter are rusty weathered and have become significantly, increasingly dolomitic upward. The lower member contains a moderately abundant, low-diversity fauna of problematic ptychopariid trilobites. The upper member contains only hyolithids and a few inarticulate brachiopods, as yet unidentified.

The siliciclastic rocks consist of well-bedded, generally thinly interstratified, very fine-grained sandstone, siltstone and cleaved shale. Sedimentary structures are generally crosslamination and lamination. The rocks are arranged in numerous, 1- to 5-m-thick coarsening-upward (CU) sequences. Quartz arenite, which displays crossbedding and undulose to planar lamination, occurs as isolated thick beds and lenses at the top of several of these sequences, especially within the upper part of the unit. Locally, scour-based arenites lie at the base of fining-upward sequences within the CU

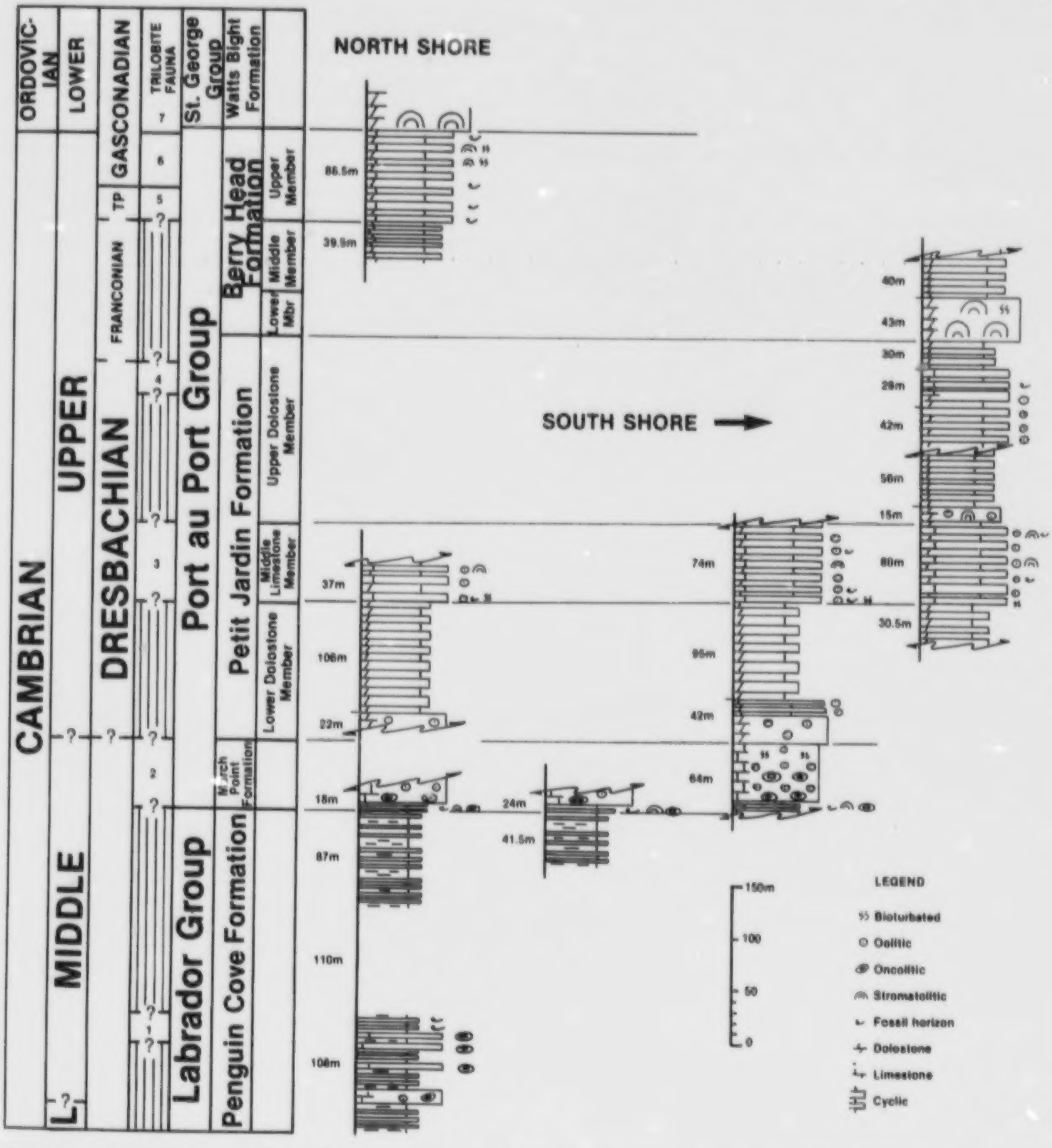
ORDOVICIAN
LOWER
GASCONADIAN
TRILOBITE FAUNA
St. George Group
Watts Bight Formation
CAMBRIAN
UPPER
MIDDLE
L
TP
FRANCONIAN
DRESBACHIAN
Port au Port Group
Labrador Group
Berry Head Formation
Upper Member
Middle Member
Lower Mbr
Petit Jardin Formation
Upper Dolostone Member
Middle Limestone Member
Lower Dolostone Member
March Point Formation
Penguin Cove Formation
NORTH SHORE
SOUTH SHORE
88.5m
39.9m
37m
106m
22m
18m
87m
110m
108m
24m
41.5m
74m
96m
42m
64m
40m
43m
30m
28m
42m
56m
15m
80m
30.5m
150m
100
50
0
LEGEND
Bioturbated
Oolitic
Oncolitic
Stromatolitic
Fossil horizon
Dolostone
Limestone
Cyclic

Figure 2. *Schematic stratigraphic sections of Cambrian rocks of Goose Arm including range of trilobite faunas. 1–*'Proliostracus / Glossopleura / Polypleuraspis' *fauna. 2–*'Olenoides longispinus / Ehmaniella cloudensis' *fauna. 3–*'Cedaria' *fauna. 4–*'Crepicephalus' *fauna. 5–*'Saukia' *fauna. 6–*'Mississiquoia' *fauna. 7–*'Symphysurina' *fauna.*

sequences. Commonly, arenites are also associated with thick beds of massive mudstone to intraclastic mudstone (slurry deposits) and mudstone enclosing impressive sandstone ball and pillow structure. Shrinkage cracks occur in many of the shale interbeds. Synsedimentary sandstone dykes intrude mudstone and interstratified rocks.

The limestone of the lower member occurs as 1- to 20-m-thick oncolitic and oölitic rudstone–grainstone units, which are commonly penetratively cleaved, obscuring structures other than thin dolostone partings and intercalation of oncolitic grainstones with non-oncolitic ones. Toward the top and bottom of the lower member, centimetre-thick, commonly lenticular, skeletal, intraclastic and oncolitic grainstone beds are intercalated within the interstratified siliciclastics. One oncolitic rudstone bed is capped by a stromatolitic mound bed. Dolomitic siltstones and very fine sandstone grade laterally into thinly bedded dolostone in the upper member. The gradation is suggested by their very similar gross appearance, dark grey phyllitic interbeds and partings as well as undulose lamination and crosslamination.

The Penguin Cove Formation is comparable to the rocks of the Hawke Bay Formation at Canada Bay (Knight and Boyce, 1987). The formation may be completely equivalent to the early Middle Cambrian Bridge Cove Member. Alternatively, only the upper member at Goose Arm is equivalent, whereas the lower member is mainly equivalent to the lower siliciclastic member at Canada Bay; this cannot be confirmed by the trilobite fauna. However, if the correlation with the lower siliciclastic member is valid, it would suggest that carbonate grainstone generation occurred in a narrow outer belt that stepped basinward as the shelf prograded during the late Early to early Middle Cambrian eustatic sea-level fall i.e., the Hawke Bay Event of Palmer and James (1980). However, if the Penguin Cove Formation correlates exclusively with the Bridge Cove Member, it suggests that the grainstone belt was only intermittently developed along the margin at that time confirming that sea level was rising throughout the time allotted to the event (see Knight and Boyce, 1987). Furthermore, the section preserved in the area is significantly thicker than the Bridge Cove Member at Canada Bay.

PORT AU PORT GROUP

The Port au Port Group in the area consists of a succession of interbedded limestone, dolostone, argillaceous shale and argillite. It can be subdivided into the March Point, Petit Jardin and Berry Head formations.

March Point Formation

The formation, which is approximately 64 m thick, is characterized by oölitic and oncolitic lime grainstones, which are dolomitized in the upper part of the formation. Beds of shale, stromatolitic lime boundstone, fossiliferous, oncolitic grainstone–packstone–rudstone and parted dolomitic limestone occur in a lower shaly member that is up to 11 m thick. Several beds of bioturbated dolomitic lime wackestone intercalate with the oölitic grainstone in the upper part of the formation. The oölitic grainstone is generally crossbedded to unevenly thinly stratified, probably indicative of small-scale crossbedding and crosslamination. In contrast, oncolitic beds are commonly structureless with some grading.

A low-diversity fauna of abundant trilobites, inarticulate brachiopods and hyolithids occurs in the lower member of the formation. Robust articulate brachiopods occur in oncolite beds in the overlying oölitic limestone. High-energy oölitic lime sand–shoal conditions prevailed in the area, in contrast to time equivalent rocks of the formation on the Northern Peninsula, where dominantly quiet water, subtidal lagoonal carbonate characterizes the formation.

Petit Jardin Formation

The Petit Jardin Formation is a thick sequence of interbedded dolostone, argillaceous dolostone, argillite and limestone arranged in repetitive centimetre- to metre- scale shallowing-upward sequences. The formation in the area comprises three members, a lower dolostone, middle limestone and upper dolostone.

The lower dolostone and upper dolostone members are quite similar. They consist of white, yellow to buff weathering, grey to pale grey, massive, microcrystalline dolostone intercalated with lesser rusty weathering, argillaceous dolostone and olive-grey to grey argillite. Both members begin with thick dolostone units of oölitic grainstone. Robust domal to slender digitate stromatolites occur with the grainstones. However, the grainstones are separated by metre-thick beds of dololaminites that, as elsewhere in the formation, comprise thin stratification and planar to crinkly lamination, which is broken in discrete layers in association with tepee structures and desiccation cracks. Lenses and thin beds of crosslamination, intraclastic grainstone and pebble beds, and frequent, shallow scour and fill structures also occur in the dololaminites.

Above these thick oölitic grainstone sequences, the members are composed of smaller cycles 0.55 to 3.0 m thick. Massive dolostone at the base of the cycles is generally featureless, but locally is clearly oölitic (especially in the lower member) and stromatolitic; however burrow-mottle fabrics do occur rarely. Dololaminites that cap most cycles are generally easily identified, but, in some cycles, the dololaminite is underlain or capped by argillite or argillaceous dolostone. Dolostone lamination and thin beds are interstratified in various proportions in both lithofacies. Where the argillite underlies a dololaminite, it has generally smooth, unbroken bedding. Dolomitic argillites that overlie the dololaminites are invariably mudcracked. The argillaceous lithofacies are commonly 20 to 90 cm thick. In the upper members, a few fossiliferous limestone beds occur in the small-scale cycles. Rocks resemble those of the middle member. A potential karst surface displaying kamenitza and irregular relief also occurs in the member.

The middle limestone member is a conspicuously cyclic unit comprising dark grey to black oölitic limestone, grey peloidal limestone, grey stromatolitic limestone and dolostone overlain by pale grey dololaminite, intraformational lime- and dolo-rudstone, and rusty weathering argillaceous dolostone to dolomitic argillite and argillite. Rare beds of parted dolomitic lime mudstone occur in the member, which in all sections begins with a burrow-mottled limestone. Erosional truncation surfaces are common, frequently cutting off stromatolite mounds. Argillaceous dolostones are common in the member, unlike the other members, and are frequently thick (up to 1.7 m). They display abundant desiccation features including deep, downward-tapering, dolostone- and carbonate sand-filled fissure cracks.

The oölitic and peloidal grainstones that commonly form the bases of cycles are characteristically crossbedded at different scales reflecting shifting dune and ripple sets; herring-bone structure occurs. Many grainstone units have reverse grading of oöid grainsize. Stromatolite mounds are mostly solid domal to upward expanding pedestal forms that rest in or upon the grainstone. Digitate structures are rare, but in some mounds they, or laminar sheet structures, form a peculiar rim around the mound core. Intraclastic lime and dolomite grainstone are thinly interstratified with dolomitic lime mudstone–dololaminite in some cycles. Intraclastic flaky grainstones derived by erosion of stromatolite, filling in one example a metre-wide channel, are a striking although not common facies in the section. They are associated with dololaminite and argillaceous dolostone facies.

The three measured sections through the member in Goose Arm indicate that correlation of cycles is difficult because there are complex lateral changes in lithofacies from section to section. Overall, the succession within the middle member is characterized by two sequences 36 and 43 m thick, each comprising a shift from subtidal to intertidal, oölitic grainstone–stromatolite-dominated cycles upward to those dominated by intertidal and supratidal dololaminite–argillaceous dolostone facies.

Berry Head Formation

The Berry Head Formation comprises three members in the area. The basal unit consists of thickly bedded, dark tan-grey, stromatolitic dolostones with chert-capped mounds. This 43-m-thick unit is succeeded by a middle member, approximately 100 m thick, that resembles the characteristic peritidal, cyclic dolostones of the Cambrian. The upper member, 87 m thick, consists of limestone with an Ordovician aspect interbedded with dololaminites characteristic of the Cambrian. This transition contains sparse trilobite faunas that indicate that the Cambro-Ordovician boundary in the autochthon lies 5 to 45 m below the base of the overlying St. George Group (Figure 3).

The thickly bedded, cherty stromatolitic dolostone of the lower member is comparable to those at the base of the formation throughout the Northern Peninsula. Although the middle member consists dominantly of pale grey dolostones, which contain abundant typical Cambrian dololaminite units (see above), it is distinguished by the cherty stromatolitic dolostone beds and by distinctive beds of crossbedded, crosslaminated and laminated pebbly dolarenite that contain frequent shallow scours and thin sheets and lenses of dololutite and in some instances reach 1.5 m in thickness.

The limestones of the upper member are characteristically dark grey, burrow-mottled, skeletal wackestone–packstone, stromatolitic boundstone, oölitic and intraclastic, skeletal grainstone–rudstone, pale grey peloidal grainstone and wavy, thinly bedded, dolomitic parted lime mudstone and dolostone. Gastropods, scattered trilobite remains and inarticulate brachiopods occur in some of these limestone beds that reach up to 2.5 m in thickness. Intercalated dololaminites can attain up to 3 m in thickness. The rocks are arranged in shallowing-upward, metre-scale cycles (Figure 3).

RELUCTANT HEAD FORMATION AND OVERLYING CAMBRIAN UNITS

The Reluctant Head Formation is an enigmatic unit comprising thin to very thinly stratified, ribbon limestone, shale, intraformational limestone conglomerate, bioturbated wackestone, intraclastic grainstone and rare microbial lime boundstone. It may be as thick as 250 m but is of limited areal extent (Gillespie, 1983).

The Reluctant Head Formation is dominated by ribbon limestone and phyllites, in which a number of intraformational conglomerates and boulder conglomerates are interspersed. The ribbon limestone generally consists of thinly intercalated grey lime mudstone and yellow-weathering dolomitic lime mudstone or dolostone. The phyllites are silvery grey, grey to dark grey. The lime conglomerates, which are interspersed in the fine-grained rocks are up to 2.8 m thick. They are matrix- to locally clast-supported, with clasts that locally reach 60 by 25 cm in size enclosed in a yellow-weathering, argillaceous dolomitic limestone matrix. Clasts are mostly slabs of ribbon limestone–phyllite, and slabs to individual lumps derived from lumpy to nodular, thin-bedded parted limestone and phyllite. However, some conglomerates have a preponderance of intraclastic grainstone clasts, as well as clasts of oölitic–intraclastic lime grainstone, graded granular lime rudstone to grainstone, and some laminated dolostone. The latter assemblage indicates the tapping of shallow-water sediments by the resedimenting gravity deposits.

In the upper 25 m of the formation, the ribbon limestone is arranged in coarsening-upward sequences 2 to 5 m thick. Ribbon limestone in these sequences is overlain by burrowed mudstone–wackestone and skeletal–intraclastic (possibly peloidal) grainstone–packstone beds. U-shaped burrows and small-scale cross stratification occur in these upper lithofacies. A digitate stromatolite-mound bed occurs at the top of one of the sequences.

The Reluctant Head Formation is conformably overlain by an unnamed unit, 42 m thick, of crossbedded dolarenites intercalated with a couple of 60 cm beds of thinly stratified, bioturbated dolostone. The allochems are probably intraclast or peloidal grains. The unit is then succeeded by further unnamed dolostones that include thick-bedded stromatolitic dolostone and dololaminites. This is succeeded by the Berry Head Formation and includes the basal cherty stromatolite marker and the upper Cambrian–Ordovician transition member of limestone and dolostone.

ST. GEORGE GROUP

Although no detailed stratigraphic work has yet been undertaken on the St. George Group in the Goose Arm–Old Man's Pond area, the four-fold stratigraphic subdivision observed elsewhere in western Newfoundland (Knight and James, 1987) is applicable in the study area. Preliminary observations suggest that the rocks resemble those of the parautochthonous successions of Canada Bay, Hare Bay and Pistolet Bay (Knight, 1986, 1987). This is marked by much

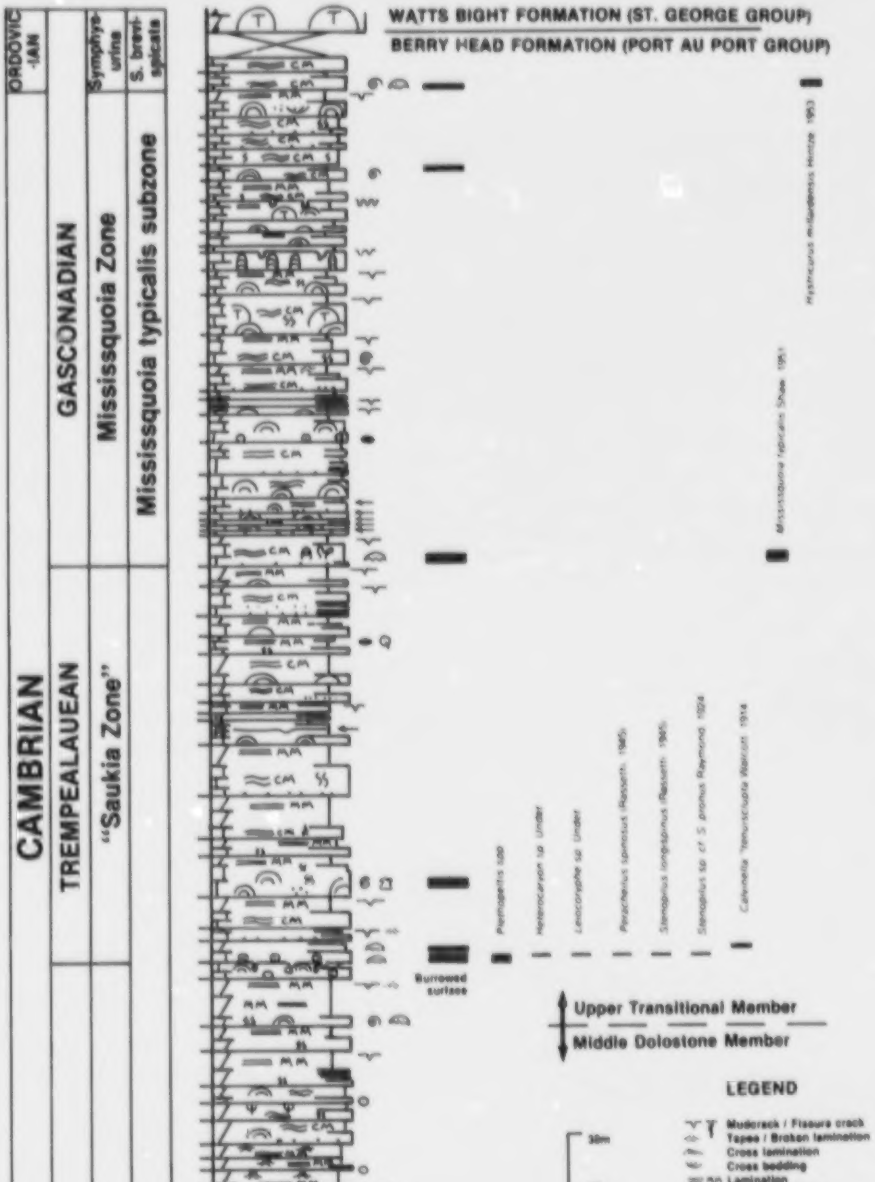
ORDOVIC-IAN
CAMBRIAN
GASCONADIAN
TREMPEALAUEAN
Symphysurina
Missisquoia Zone
"Saukia Zone"
S. brevispicata
Missisquoia typicalis subzone
WATTS BIGHT FORMATION (ST. GEORGE GROUP)
BERRY HEAD FORMATION (PORT AU PORT GROUP)
cm
MM
T
Burrowed surface
Patterned dolomite
Plethopeltis spp
Heterocaryon sp Under
Leiocoryphe sp Under
Plesiochasmus spinosus (Rasetti 1945)
Stenopilus longispinus (Rasetti 1945)
Stenopilus sp cf S. pronus Raymond 1924
Calvinella 'tenuisculpta' Walcott 1914
Mississquoia typicalis Shaw 1951
Hystricurus millardensis Hintze 1953
Upper Transitional Member
Middle Dolostone Member
LEGEND
30m
25
20
15m
10
5
0
Mudcrack / Fissure crack
Tepee / Broken lamination
Cross lamination
Cross bedding
Lamination
Thin stratification
Thrombolite mounds
Stromatolite
Bioturbation
Quartz sand
Chert
Oolitic
Grainy, pebbly
Trilobite
Gastropod
Brachiopod
Truncation surface
Possible karst
Collapse breccia
Cycle boundary
Small Scale cycle
Dolostone
Limestone
Shaly dolostone
Fossil horizon

Figure 3. *Biostratigraphy and lithostratigraphy of the Berry Head Formation, north shore, Goose Arm.*

less dolomitization of the Watts Bight and Catoche formations, large metazoan–microbial mounds in the Watts Bight and Catoche formations, the white peloidal limestone of the Costa Bay Member and the presence of intercalated limestone and dolostone in the Aguathuna Formation.

MIDDLE ORDOVICIAN STRATA

Preliminary observations indicate that massive, blue-grey limestone of the Table Point Formation rests upon the St. George Group; the St. George Unconformity has yet to be located. The base of the unit (Spring Inlet Member) is marked by intercalated limestone and dolostone including beds of oncolitic, skeletal-intraclastic lime grainstone and rudstone. Younger rocks of the Goose Tickle Group have only been seen in structural contact with the carbonate succession in the area. For the most part, it seems to be incorporated in a strongly deformed melange, together with black shales and thin black limestone beds of the Table Cove and Black Cove formations (Stenzel *et al.*, 1990) along the western edge of the carbonate terrane.

BIOSTRATIGRAPHY OF THE PENGUIN COVE FORMATION, RELUCTANT HEAD FORMATION AND PORT AU PORT GROUP

Although the geology of the Hughes Brook–Goose Arm area was first outlined by Lilly (1961, 1963), paleontological information from the Cambrian–Ordovician rocks has been distinctly lacking. Levesque (1977, page 79) reported unidentified early Middle Cambrian ptychopariid trilobite and inarticulate brachiopod fragments from the base of his Wolf Brook Formation (March Point Formation, *this report*) on the north and south shores of Goose Arm. Later, Boyce *in* Gillespie (1983, page 22, Plate 1) illustrated the late Middle Cambrian trilobite *Kootenia cloudensis* Howell, 1943, collected by Gillespie from an inland oncolitic limestone exposure of the March Point Formation (our usage) between Goose Arm and Old Man's Pond.

In 1983, at the request of Westfield Minerals, the authors rendered stratigraphic assistance in Goose Arm. As a result, seven previously unreported fossiliferous localities were sampled (Glover *in* Wilkinson, 1983, Appendix A, page 13, Figure 8); Boyce discovered faunas indicative of the early Late Cambrian Dresbachian Stage *(Cedaria–Crepicephalus* zones) and the late Late Cambrian Trempealeauan Stage *(Saukia* Zone). In 1990, more assiduous biostratigraphic sampling resulted in the discovery of many additional macrofossil localities. This work was done in concert with detailed lithostratigraphic sectioning. Fifty-seven horizons yielded macrofossils, principally trilobites and inarticulate brachiopods. Twenty-two collections were obtained from the north shore of Goose Arm, thirty-five from the south shore. In addition, fourteen macrofossil collections were obtained from the upper part of the Reluctant Head Formation exposed on the Hughes Brook–Goose Arm logging road system south of Old Man's Pond.

PENGUIN COVE FORMATION

The lower member of the Penguin Cove Formation is characterized by a low diversity fauna of moderately abundant, (problematic) ptychopariid trilobites, including a possible new species of *Yohoaspis* (an early Middle Cambrian *Albertella* Zone genus). The fauna of the lower member is probably correlative with that of the *Proliostracus* Zone in the Hawke Bay Formation (Bridge Cove member) of Canada Bay (Knight and Boyce, 1987).

The upper member of the Penguin Cove Formation contains only hyolithids and a few inarticulate brachiopods, as yet unidentified. It may correlate with the strata of the *Glossopleura* and *Polypleuraspis* zones in the Hawke Bay Formation (Bridge Cove member) of Canada Bay (Knight and Boyce, 1987).

RELUCTANT HEAD FORMATION

The newly discovered trilobite and inarticulate brachiopod fauna from the top of the Reluctant Head Formation includes the agnostid species *Kormagnostus seclusus* (Walcott, 1884). According to Robison (1988, page 45), this species ranges from the late Middle Cambrian *Lejopyge laevigata* Zone (i.e., latest *Bolaspidella* Zone) to the early late Cambrian *Glyptagnostus stolidotis* Zone (i.e., *Crepicephalus* Zone).

MARCH POINT FORMATION

The March Point Formation in the Goose Arm–Hughes Brook area has, so far, yielded only two trilobite taxa, along with inarticulate brachiopods and some hyolithids. As stated above, Gillespie (1983) obtained *Kootenia cloudensis* Howell, 1943 from an inland exposure. Along Goose Arm itself, *Spencella proavita* (Howell, 1943) is the only trilobite thus far identified from the March Point Formation. These two species indicate a correlation with the late Middle Cambrian *Olenoides longispinus* and *Ehmaniella cloudensis* zones of the March Point Formation in the Canada Bay area (Knight and Boyce, 1987).

PETIT JARDIN FORMATION

Trilobite faunas correlative with the Dresbachian (early Late Cambrian) *Cedaria* Zone were recovered from the middle limestone member of the Petit Jardin Formation on the north and south shores of Goose Arm. Species recovered include:

Blountiella? johnsoni Troelsen, 1947
Kingstonia ara (Walcott, 1924)
Komaspidella sp. undet.
Lonchocephalus? sp. undet.
Talbotina degrasensis Lochman, 1938
Welleraspis newfoundlandensis Lochman, 1938

Lochman (1938) described and illustrated *Kingstonia ara* (Walcott, 1924), *Talbotina degrasensis* Lochman, 1938 and

Welleraspis newfoundlandensis Lochman, 1938 from the Petit Jardin Formation on the Port au Port Peninsula, western Newfoundland. *Welleraspis newfoundlandensis* Lochman, 1938 also occurs in *Cedaria* Zone age strata of the Holm Dal Formation in central North Greenland (Robison, 1988). *Blountiella? johnsoni* Troelsen, 1947 was originally described from Bonne Bay, western Newfoundland (Troelsen, 1947).

Definitive Dresbachian *Crepicephalus* Zone trilobites were collected from one horizon only, on the south shore of Goose Arm in the upper dolostone member of the Petit Jardin Formation. Pygidia of the following species were recovered from a white limestone:

Crepicephalus rivus Kindle, 1948
Kingstonia sp. undet.
Tricrepicephalus texanus (Shumard, 1861)

Crepicephalus rivus Kindle, 1948 and *Tricrepicephalus texanus* (Shumard, 1861) also occur in the Murphy Creek Formation of Quebec (Kindle, 1948). *Tricrepicephalus texanus* (Shumard, 1861) is a particularly widespread species, which ranges from the late *Cedaria* Zone to the *Crepicephalus* Zone.

Late Dresbachian and Franconian (medial Late Cambrian) trilobites have yet to be recorded from the Goose Arm area.

BERRY HEAD FORMATION

The most significant result of the investigations in Goose Arm may be the discovery of a fossiliferous Cambrian–Ordovician boundary interval in the Berry Head Formation. Elsewhere in western Newfoundland, this interval generally comprises unfossiliferous dolostone.

Three distinct trilobite faunas (indicative of the *Saukia*, *Mississquoia* and *Symphysurina* zones) are present in limestone beds on the north shore of Goose Arm; unidentified gastropods and less common inarticulate brachiopods also occur with the trilobites.

The oldest fauna is correlative with the Trempealeauan (latest Cambrian) *Saukia* Zone (*Saukiella junia* and *Saukiella serotina* subzones) and is chartacterized by the following trilobites:

Calvinella sp. cf. *C. tenuisculpta* Walcott, 1914
Heterocaryon sp. undet.
Leiocoryphe sp. undet.
Peracheilus spinosus (Rasetti, 1945)
Plethopeltis spp.
Stenopilus longispinus (Rasetti, 1963)
Stenopilus sp. cf. *S. pronus* Raymond, 1924

Peracheilus spinosus (Rasetti, 1945) and *Stenopilus longispinus* (Rasetti, 1963) occur in the *Keithia schucherti* faunas of the Levis Formation of Quebec and the Cow Head Group of western Newfoundland (Rasetti, 1944, 1945, 1963; Ludvigsen *et al.*, 1989).

The middle fauna contains *Mississquoia typicalis* Shaw, 1951. This widespread taxon generally[1] characterizes the *Mississquoia typicalis* Subzone of the *Mississquoia Zone* of Vermont (Shaw, 1951), Texas (Winston and Nicholls, 1967), Oklahoma (Stitt, 1971, 1977, 1983), Utah and Nevada (Taylor, 1971), South Dakota (Hu, 1973), New York (Taylor and Halley, 1974), Alberta and British Columbia (Dean, 1977; Westrop, 1986).

The youngest fauna of the Berry Head Formation contains *Hystricurus millardensis* Hintze, 1953. This widespread species generally[2] characterizes the *Symphysurina brevispicata* Subzone of the *Symphysurina* Zone of Utah (Hintze, 1953), Texas (Winston and Nicholls, 1967), Oklahoma (Stitt, 1971, 1977, 1983), South Dakota (Hu, 1973), New York (Taylor and Halley, 1974) and Idaho (Taylor and Landing, 1982).

THE CAMBRIAN–ORDOVICIAN BOUNDARY IN GOOSE ARM

In western Newfoundland, *Mississquoia typicalis* Shaw, 1951 and *Hystricurus millardensis* Hintze, 1953 also occur in the allochthonous Cow Head Group at the Broom Point South section (Fortey and Skevington, 1980; Fortey *et al.*, 1982; Fortey, 1983; Barnes, 1988). The currently favoured Cambrian–Ordovician global Boundary 'point' is the base of the *Cordylodus lindstromi* (conodont) Zone (Barnes, 1988, page 408, Figure 12). At the Broom Point South section, this lies between the occurrences of the two trilobite species (Barnes, 1988, page 393, Figure 6). Consequently, at Goose Arm, the Cambrian–Ordovician Boundary 'point' may also lie anywhere between the occurrences of *Mississquoia typicalis* Shaw, 1951 and *Hystricurus millardensis* Hintze, 1953. This represents a problematic interval of about 40 m (a distance of 5 to 45 m below the base of the Watts Bight Formation). Further trilobite (and conodont) sampling and analysis is required to test this hypothesis.

PALEOGEOGRAPHY OF THE CAMBRIAN SHELF

The combination of well-dated sequences at Goose Arm adjacent to the dated facies-distinct sequence in the Reluctant Head Thrust slice provides a unique opportunity to model part of the ancient Cambrian shelf in western Newfoundland. The shelf evolved essentially from a siliciclastic to a carbonate ramp. The evolution to a rimmed platform may have only occurred by the late Cambrian.

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[1] In Oklahoma and Texas, *Mississquoia typicalis* Shaw, 1951 also ranges up into the *Symphysurina brevispicata* Subzone of the *Symphysurina Zone* (Stitt, 1977, Figures 9 and 10).

[2] In Oklahoma, *Hystricurus millardensis* Hintz, 1953 also ranges into the overlying *Symphysurina bulbosa* and *Symphysurina woosteri* subzones (Stitt, 1983, Figure 7).

1) EARLY MIDDLE CAMBRIAN SILICICLASTIC SHELF

The thinly but well-stratified, fine-grained siliciclastic sediments of the Penguin Cove Formation were probably supplied by low density, decelerating traction currents across a gentle slope. The presence of isolated thick beds of quartz arenite, several oncolitic grainstone beds and metre-thick units, regularly punctuating the lower member of the formation suggests that the shelf was not deep. This conclusion is also supported by the stromatolite bed lying upon one oncolite bed.

Regular carbonate deposition within a dominantly siliciclastic system hints that they may reflect small-scale eustatic sea-level fluctuations superimposed upon a longer term eustatic sea-level cycle. This would suggest that the oncolite–oölite sands formed during sea-level rise that would have drowned shorelines and dampened terrigenous input. In the oldest beds of the member, the grainstone beds may have been storm beds swept from a shoal complex on to the siliciclastic ramp. The problem with this is the presence of the stromatolite, which, unless considered as subtidal, would mean that the carbonates represent shallowing events, when an outer oncolitic–oölitic carbonate shoal belt shifted in board upon the ramp to displace siliciclastic facies.

On a regional scale, the repetitive presence of carbonate grainstone in the Goose Arm section, coupled to those that are interspersed in co-eval successions at Canada Bay, indicate that sea-level rise continued regionally in western Newfoundland throughout the early Middle Cambrian. Its effect was muted by the volume of terrigenous input, suggesting that the latter was primarily controlled by tectonically induced source area uplift.

2) LATE MIDDLE CAMBRIAN TO LATE CAMBRIAN CARBONATE RAMP

Transgression during the late Middle Cambrian preceded widespread carbonate sedimentation. In the Goose Arm area, the shallow shelf facies comprised two end members. Thick, generally non-cyclic oölitic grainstone shoal complexes dominated the March Point Formation and occupy the lower parts of the lower and upper dolostone members of the Petit Jardin Formation. The rest of the Petit Jardin Formation comprises shallowing-upward, metre-scale peritidal sequences. The cycles comprise tidal-dominated oölite sands and stromatolite biostromes (probably subtidal to lower intertidal). They accreted to tidal flats consisting of intertidal dololaminites and argillaceous dolostones, the latter possibly verging on a supratidal setting or forming on the inner, landward side of the tidal flat. The significance within the dolostone-dominated succession of the Petit Jardin Formation of the limestone plus trilobite fauna in the middle limestone member may suggest that there was a change on the shelf from restricted to less restricted conditions, perhaps linked to relative sea-level rise.

The sediments of the Reluctant Head Formation are typical of a ramp slope setting that shallowed into a dolomitized carbonate sand complex and then with time into typical peritidal shelf dolostones. Resedimented limestone conglomerates in the ribbon limestone and shale indicate some reworking of slope sediments, but at least one of the conglomerates contains clasts derived by reworking of oölitic grainstone and dolostone, indicating a peritidal source. The dolomitized lime sands at the base of the unnamed dolostone above the Reluctant Head Formation are not oölitic, however, but intraclastic and peloidal. The ribbon bedding, lack of slump folds and beds and the general shallowing-upward trend suggest that the Reluctant Head Formation was deposited upon a prograding ramp shelf. The Dresbachian trilobites recovered from the top of the formation indicate that the formation is at least partly equivalent to the Petit Jardin Formation. The exact position is not certain however, but the fauna plus stratigraphic reasons suggest that the formation probably straddles the lower members of the formation and that the carbonate sand shoal may correlate with the lower part of the upper dolostone member. This is supported by the position of the shoal facies at the base of the unnamed peritidal dolostone sequence that is capped by the Berry Head Formation, because the cherty stromatolite member at the base of the latter is a regional marker from autochthon to parautochthon. This must indicate that the evolution to a platform occurred late in the Cambrian (i.e., post Dresbachian).

STRUCTURE OF THE GOOSE ARM AREA

Preliminary mapping of the Goose Arm–Old Man's Pond area indicates that deformation of the carbonate sequence occurred during and following the emplacement of several thrust slices into the area. The two most obvious thrusts are the Reluctant Head Thrust (RHT) in the east and the Penguin Head Thrust (PHT) at the western margin of the autochthon (Figure 4). Binocular viewing of recumbently folded strata at Raglan Head and mapping in the Old Man's Pond area suggest that several other thrusts occur in the area (see also Glover, in Wilkinson, 1983).

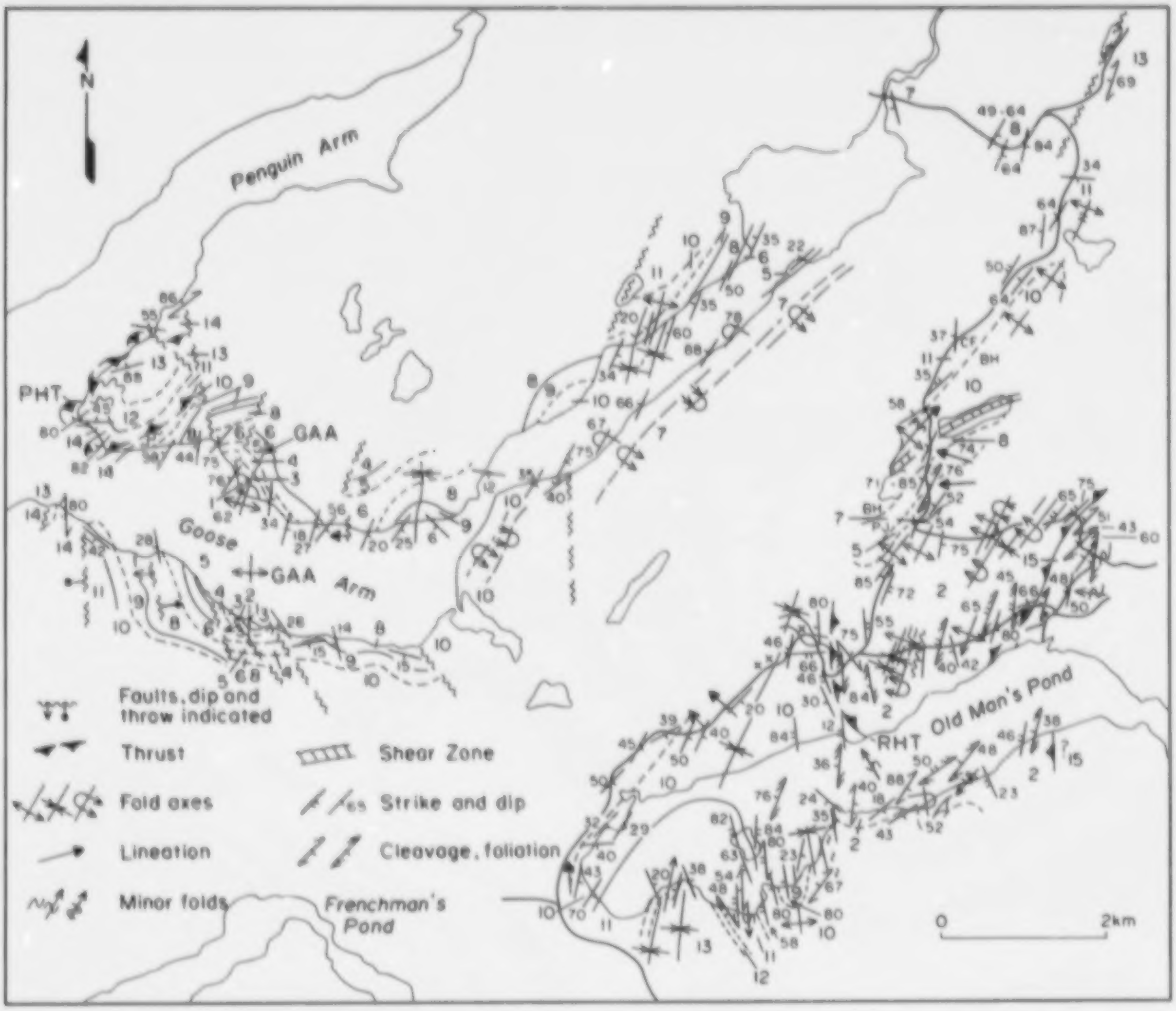
The Goose Arm carbonate succession has undergone polyphase deformation. This includes:

PHASE 1

Phase 1 (P1) structures include the west-directed thrusts and the associated development of bedding co-planar foliation in intercalated limestone marble and dolostone of the Port au Port, St. George and Table Head groups, penetrative cleavage (transposed bedding) in the Reluctant Head Formation and small-scale recumbent folds. Dolostone beds were boudinaged to dismembered and locally intensely flattened in the plane of the marble foliation.

PHASE 2

Phase 2 (P2) consists of deformation only within the Reluctant Head Thrust zone. The early foliation is folded by


N
Penguin Arm
PHT
GAA
Goose Arm
GAA
Old Man's Pond
RHT
BH
Frenchman's Pond
0
2km
Faults, dip and throw indicated
Thrust
Shear Zone
Fold axes
Strike and dip
Lineation
Cleavage, foliation
Minor folds

LEGEND

15	Old Man's Pond Allochthon

MIDDLE ORDOVICIAN

14	Undivided Table Cove Formation/Goose Tickle Group

TABLE HEAD GROUP

13	Table Point Formation

LOWER ORDOVICIAN

ST. GEORGE GROUP

12	Aguathuna Formation
11	Catoche Formation
10	Boat Harbour Formation
9	Watts Bight Formation

MIDDLE TO UPPER CAMBRIAN

PORT AU PORT GROUP

8	Berry Head Formation

Petit Jardin Formation

7	*undivided*
6	*Upper dolostone*
5	*Middle limestone*
4	*Lower dolostone*

3	March Point Formation
2	Reluctant Head Formation

LABRADOR GROUP

1	Penguin Cove Formation

Figure 4. *Preliminary geological map of Goose Arm and Old Man's Pond area.*

small-scale west-directed recumbent folds. Earlier folds were refolded and sheath folds generated at the sole of the Reluctant Head Thrust.

PHASE 3

Phase 3 (P3) consists of folding of earlier P1 structures by east-verging, northeast-trending folds associated with a spaced, axial-planar cleavage. The folds are markedly recumbent adjacent to the Old Man's Pond Allochthon. Crenulation of the P1 cleavage has occurred.

Phase 1 westward-directed thrusting superimposed Reluctant Head Formation over St. George Group limestones (Reluctant Head Thrust) and transported middle St. George Group to Table Point Formation limestone above Taconic flysch and deepwater shales and carbonates (Table Cove Formation) along the PHT. At Penguin Head and the south shore of Goose Arm, the intensely deformed Middle Ordovician flyschoid rocks of the footwall have a dismembered aspect that suggests they were incorporated in a melange before or during the emplacement of PHT thrust. However, it is improbable that the PHT is a large melange block as suggested by Waldron (1985).

At Old Man's Pond, intense deformation within the Reluctant Head Formation at the sole of the RHT developed a penetrative, phyllitic cleavage (transposed bedding, S1) and small-scale recumbent structures that were subsequently refolded, and locally as sheath folds. Polyphase deformation is also present in the Petit Jardin Formation and the St. George Group along the south shore of Old Man's Pond. An early foliation (S1), which is well developed in limestones interbedded with dolostones in these rocks, is interpreted to have formed during P1 thrusting. It is roughly co-planar with bedding and locally is folded by small-scale recumbent, west-facing folds (F2). Dolostone beds are locally pinched by rows of articulated boudins during extension. The bedding and early foliation is folded about P3 upright to overturned, northeast-trending structures. These folds steepened the F2/?F3 folds in the thrust sole and P3 cleavage, which dips to the west, crenulates the earlier penetrative east-dipping cleavage. Strengthening of the east-verging domain occurs eastward in the RHT as the latest folds gradually become recumbent adjacent to the Old Man's Pond Allochthon.

Northeast-trending, east-verging folds deform the PHT and its hanging- and footwalls. Hanging-wall bedding and thrust attitudes are basically co-planar in the east, and small-scale structures suggest some eastward-directed shear along the thrust contact. The key to understanding the relationship at Penguin Head however, occurs along the shore of Penguin Arm. There, the footwall melange and Taconic flysch structurally overlies to abuts vertically against stratigraphically, northward-younging St. George and Table Head group rocks. This relationship, plus some anomalous fold trends in the Aguathuna Formation of the hanging-wall, is best explained by folding the thrust and a west-verging hanging-wall rollover about the northeast-trending folds.

The structural relationship between the RHT and the Old Man's Pond Allochthon north of the pond is obscured by overburden. However, it appears that the RHT may lie structurally upon the allochthon, unless a steep fault separates the two terranes. Likewise, the trace of the RHT south of the pond is uncertain. North toward Goose Arm, the RHT appears to intersect a shear zone that trends 210° and dips at 82° northwest. Kinematic indicators in the shear zone suggest steep oblique slip associated with dolomite augen and folded boudins, indicating the north hanging wall has been upthrust. The shear zone appears to cut out all of the Watts Bight Formation and the lower part of the overlying Boat Harbour Formation, perhaps totalling 200 m. However, bedding trends in the carbonates on either side of the shear zone do not diverge.

Not all northeast-trending folds in the area verge eastward. The Goose Arm Anticline (GAA) has a steeply dipping west limb and east-dipping, axial-planar cleavage. West-verging recumbent folds occur in the St. George Group at Raglan Head and in Cambrian strata on the east side of inner Goose Arm. These folds probably formed in the footwall of two thrusts including the Window Pond Thrust of Glover (in Wilkinson, 1983). If this is so, it suggests that the GAA is a related structure.

Most high-angle faults trend northwest and dip southwest between 66 and 80°. They are reverse faults marked by generally sharp fault planes, very little fault breccia only in the hanging wall, and drag folding in the footwall. They offset folds and thrusts.

REFERENCES

Barnes, C.R.

1988: The proposed Cambrian–Ordovician global boundary stratotype and point (GSSP) in western Newfoundland, Canada. Geological Magazine, Volume 125, pages 381-414.

Cawood, P.A. and Williams, H.

1988: Timing and character of orogenic events in west Newfoundland: implications for crustal structure. *In* Lithoprobe East, Report of Transect Meeting, Memorial University of Newfoundland, St. John's, Newfoundland, pages 58-60.

Chow, N.

1986: Sedimentology and diagenesis of Middle and Upper Cambrian platform carbonates and siliciclastics, Port-au-Port Peninsula, western Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, 458 pages.

Cowan, C.A. and James, N.P.

1989: Stratigrapy and sedimentology of the Port au Port Group (Middle to Upper Cambrian), western Newfoundland: preliminary results. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 55-61.

Dean, W.T.
1977: The Early Ordovician trilobite genus *Mississquoia* Shaw 1951 in the southern Canadian Rocky Mountains of Alberta and British Columbia. Geological Survey of Canada, Paper 76-33, 7 pages.

Fortey, R.A.
1983: Cambrian–Ordovician trilobites from the boundary beds in western Newfoundland and their phylogenetic significance. *In* Special Papers in Palaeontology, Number 30, pages 23-27.

Fortey, R.A., Landing, E. and Skevington, D.
1982: Cambrian–Ordovician boundary sections in the Cow Head Group, western Newfoundland. *In* The Cambrian–Ordovician boundary: sections, fossil distributions, and correlations. *Edited by* M.G. Bassett and W.T. Dean. National Museum of Wales, Geological Series Number 3, Cardiff, pages 95-129.

Fortey, R.A. and Skevington, D.
1980: Correlation of Cambrian–Ordovician boundary between Europe and North America: new data from western Newfoundland. Canadian Journal of Earth Sciences, Volume 17, pages 382-388.

Gillespie, R.T.
1983: Stratigraphic and structural relationships among rock groups at Old Man's Pond, west Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, 198 pages.

Hintze, L.F.
1953: Lower Ordovician trilobites from western Utah and eastern Nevada. Utah Geological and Mineralogical Survey, Bulletin 48, 249 pages.

Hu, C.-H.
1973: Description of basal Ordovician trilobites from the Deadwood Formation, northern Black Hills, South Dakota. Proceedings of the Geological Society of China, Volume 16, pages 85-95.

Kindle, C.H.
1948: Crepicephalid trilobites from Murphy Creek, Quebec and Cow Head, Newfoundland. American Journal of Science, Volume 246, pages 441-451.

Knight, I.
1986: Ordovician sedimentary strata of the Pistolet Bay and Hare Bay area, Great Northern Peninsula, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 147-160.

1987: Geology of the Roddickton (12I/16) map area. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 343-357.

Knight, I. and Boyce, W.D.
1987: Lower to Middle Cambrian terrigenous-carbonate rocks of Chimney Arm, Canada Bay: lithostratigraphy, preliminary biostratigraphy and regional significance. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, page 359-365.

Knight, I. and James, N.P.
1987: Stratigraphy of the St. George Group, (Lower Ordovician) western Newfoundland; the interaction between eustasy and tectonics. Canadian Journal of Earth Sciences, Volume 24, pages 1927-1952.

Levesque, R.
1977: Stratigraphy and sedimentology of Middle Cambrian to Lower Ordovician shallow water carbonate rocks, western Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, 276 pages.

Lilly, H.D.
1961: Geology of the Goose Arm–Hughes Brook area. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, 123 pages.

1963: Geology of Hughes Brook–Goose Arm area. Memorial University of Newfoundland, Geology Report 2, 123 pages.

Lochman, C.
1938: Middle and Upper Cambrian faunas from western Newfoundland. Journal of Paleontology, Volume 12, pages 461-477.

Ludvigsen, R., Westrop, S.R. and Kindle, C.H.
1989: Sunwaptan (Upper Cambrian) trilobites of the Cow Head Group, western Newfoundland, Canada. Palaeontographica Canadiana, Number 6, 175 pages.

McKillop, J.M.
1963: Geology of the Corner Brook area, Newfoundland with emphasis on the carbonate deposits. Memorial University of Newfoundland, St. John's, Geology Report No. 1, 102 pages.

Palmer, A.R. and James, N.P.
1980: The Hawke Bay event: a circum-Iapetus event of Lower Cambrian age. *In* The Caledonides in the USA. *Edited by* D.R. Wones. IGCP, Blacksburg, Virginia, Virginia Polytechnic Institute and State University, Memoir 2, pages 15-18.

Rasetti, F.
1944: Upper Cambrian trilobites from the Levis conglomerate. Journal of Paleontology, Volume 18, pages 229-258.

1945: New Upper Cambrian trilobites from the Levis conglomerate. Journal of Paleontology, Volume 19, pages 462-478.

1963: Additions to the Upper Cambrian fauna from the conglomerate boulders at Levis, Quebec. Journal of Paleontology, Volume 37, pages 1009-1017.

Robison, R.A.
1988: Trilobites of the Holm Dal Formation (late Middle Cambrian), central North Greenland. *In* Stratigraphy and Paleontology of the Holm Dal Formation (late Middle Cambrian), central North Greenland. *Edited by* J.S. Peel. Meddelelser om Grønland, Geoscience 20, pages 23-103.

Schuchert, C. and Dunbar, C.O.
1934: Stratigraphy of western Newfoundland. Geological Society of America, Memoir 1, 123 pages.

Shaw, A.B.
1951: The paleontology of northwestern Vermont. I. New Late Cambrian trilobites. Journal of Paleontology, Volume 25, pages 97-114.

Stenzel, S.R., Knight, I. and James, N.P.
1990: Carbonate platform to foreland basin; revised stratigraphy of the Table Head Group (Middle Ordovician), western Newfoundland. Canadian Journal of Earth Sciences, Volume 27, pages 14-26.

Stitt, J.H.
1971: Late Cambrian and earliest Ordovician trilobites, Timbered Hills and Lower Arbuckle Groups, western Arbuckle Mountains, Murray County, Oklahoma. Oklahoma Geological Survey, Bulletin 110, 83 pages.

1977: Late Cambrian and earliest Ordovician trilobites Wichita Mountains area, Oklahoma. Oklahoma Geological Survey, Bulletin 124, 79 pages.

1983: Trilobites, biostratigraphy and lithostratigraphy of the McKenzie Hill Limestone (Lower Ordovician), Wichata and Arbuckle Mountains, Oklahoma. Oklahoma Geological Survey, Bulletin 134, 54 pages.

Taylor, M.E.
1971: Biostratigraphy of the Upper Cambrian (Upper Franconian-Trempealeauan Stages) in the central Great Basin, Utah and Nevada. Unpublished Ph.D. thesis, University of California, Berkeley, 428 pages.

Taylor, M.E. and Halley, R.B.
1974: Systematics, environment and biogeography of some Late Cambrian and Early Ordovician trilobites from eastern New York State. United States Geological Survey, Professional Paper 834, 38 pages.

Taylor, M.E. and Landing, E.
1982: Biostratigraphy of the Cambrian–Ordovician transition in the Bear River Range, Utah and Idaho, western United States. *In* The Cambrian–Ordovician boundary, sections, fossil distributions, and correlations. *Edited by* M.G. Bassett and W.T. Dean. National Museum of Wales, Geological Series Number 3, Cardiff, pages 181-191.

Troelsen, J.C.
1947: A new Cambrian fauna from western Newfoundland. American Journal of Earth Science, Volume 245, pages 537-544.

Waldron, J.W.F.
1985: Structural history of continental margin sediments beneath the Bay of Islands Ophiolite, Newfoundland. Canadian Journal of Earth Sciences, Volume 22, pages 1618-1632.

1988: Structural studies in the Old Man's Pond area, western Newfoundland. *In* Lithoprobe East, Report of Transect Meeting, Memorial University, St. John's, Newfoundland, pages 61-63.

Westrop, S.R.
1986: Trilobites of the Upper Cambrian Sunwaptan Stage, southern Canadian Rocky Mountains, Alberta. Palaeontographica Canadiana, Number 3, 179 pages.

Wilkinson, R.
1983: Brinco Goose Arm Concession. NTS 12H/4, 12H/7. Report of Exploration, 1983. Westfield Minerals Limited, 29 pages. [12H(839)]

Winston, D. and Nicholls, H.
1967: Late Cambrian and Early Ordovician faunas from the Wilberns Formation of central Texas. Journal of Paleontology, Volume 41, pages 66-96.

NOTE: Geological Survey Branch file numbers are included in square brackets.

Current Research (1990) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 90-1, pages 155-[illegible]

GEOLOGICAL DEVELOPMENT OF THE EXPLOITS AND NOTRE DAME SUBZONES IN THE NEW BAY AREA (PARTS OF NTS 2E/6 AND 2E/11), MAP AREA, NOTRE DAME BAY, NEWFOUNDLAND

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ABSTRACT

In the New Bay area, lower and middle Paleozoic rocks of the Exploits and Notre Dame subzones are disposed about an intra-Dunnage Zone oroclinal flexure in the north-central Newfoundland Appalachians. Strata of Ordovician and Silurian age accumulated in tectonically active basins, whose depocentres were possibly controlled by a migrating crustal bulge or syndepositional arch.

Progressive regional (post-Llandovery) deformation was focussed on basin-margin fault zones. Prior to late-stage transcurrent faulting, deformation proceeded in individual structural domains, regionally oriented either northwest or northeast. Periclinal anticlinoria or synclinoria, bounded by convergent or divergent, conjugate thrusts, evolved into basins and domes outlined by folded faults.

Syndepositional faults, postulated to occur where thrusts show variable amounts of up-dip contractional displacement, may be important features controlling the distribution of felsic pyroclastic domes and related base-metal mineralization. Reactivated synvolcanic or synsedimentary faults are the preferred location of syntectonic multiple intrusions. Screens of gabbro–diorite are variably altered and mineralized, particularly in the Exploits Subzone.

INTRODUCTION

The New Bay area in north-central Newfoundland is underlain, for the most part, by Paleozoic strata belonging to the Exploits and Notre Dame subzones of the Appalachian Dunnage Zone (Williams, *et al.*, 1988; Swinden *et al.*, 1988). The Red Indian Line, which is probably the southeastern limit of sub-Dunnage Zone Grenvillian basement at mid-crustal depths (Keen *et al.*, 1986; Marillier *et al.*, 1989), is manifested within the map area as a 2- to 3-km-wide mylonite zone that contains discontinuous belts of scaly-foliated melange. Throughout the New Bay area, the Red Indian Line separates fossil-bearing, Ordovician and Silurian volcano-sedimentary rocks of the Exploits Subzone to the south, from unfossiliferous and locally undated, volcano-sedimentary and hypabyssal rocks of the Notre Dame Subzone to the north (Figure 1). Progressively deformed constituents of the Red Indian Line structural zone include mylonitic units from both subzones and fault planes of regionally developed thrusts such as the Lukes Arm (Horne and Helwig, 1969; Blewett, 1989), Sops Head (Nelson, 1981; Bostock, 1988), New Bay (Helwig, 1967; Dean, 1977) and Northwest Arm faults (Helwig, 1967).

AGE, DISTRIBUTION AND REGIONAL RELATIONSHIPS

The distribution of lithostratigraphic units in the New Bay area is shown at 1:250,000 scale in Figure 1. Within this region, Units 1 to 4 are fault-bounded at exposed contacts, are apparently unfossiliferous and do not contain rocks for which absolute isotopic ages are available. They are assigned an Ordovician or earlier age based on previous regional correlations with units in other areas (Dean, 1977, 1978; Swinden *et al.*, 1988). Unit 1 has been correlated with the Late Cambrian Moretons Harbour Group. Unit 2, which includes the presumed Ordovician South Lake ophiolite, has been termed the South Lake Igneous Complex. Unit 3 comprises the main tract of the Cottrells Cove Group, originally postulated as Silurian in age (Dean and Strong, 1977), but more recently correlated with the Early Ordovician (Dunning *et al.*, 1987) Buchans and Roberts Arm groups. Unit 4 represents a small part of the Wild Bight Group, the uppermost portion of which probably correlates with the stratigraphically highest (Early Ordovician) parts of Unit 5.

Each of Units 5 through 8 contains one or more stratigraphic intervals that yield shelly or graptolitic faunas (Dean, 1977; Williams, *in press;* W.D. Boyce, personal communication, 1990). These fossils indicate a shallow and/or deep-marine origin for their siliciclastic and calcareous host rocks, and a probable Llanvirn–Llandovery stratigraphic range for Units 5 through 8. Volumetrically, turbiditic shale, sandstone and conglomerate interstratified with pillowed, brecciated or scoraceous, mafic lava predominate most of the Llanvirn–Llandovery units. Although primary subunits and resedimented megaclasts of iron formation and chert, reefal-, shelly- and conodont-bearing limestone, sulphide-rich

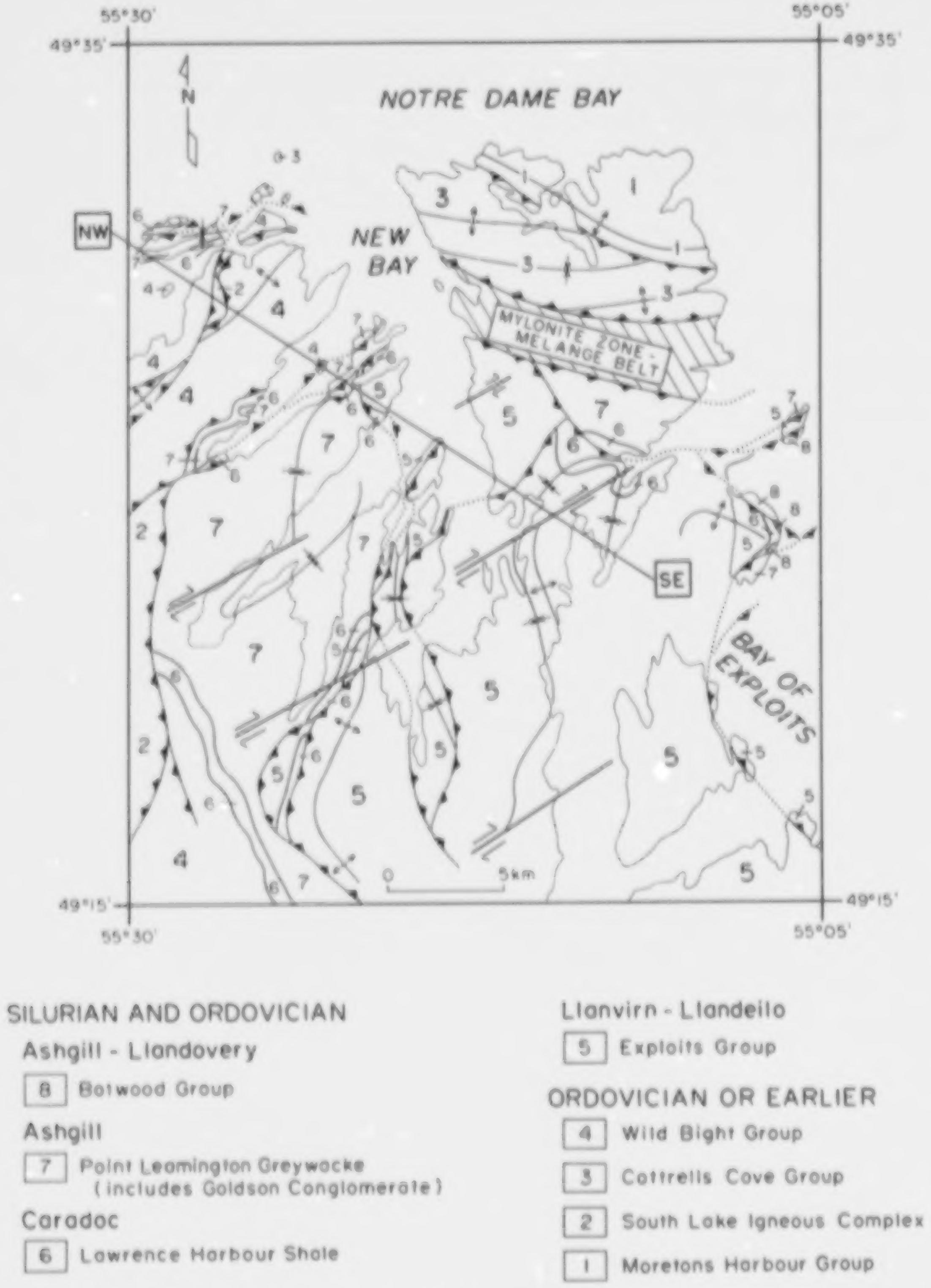
55°30'
55°05'
49°35'
49°35'
N
NOTRE DAME BAY
NEW BAY
NW
MYLONITE ZONE - MELANGE BELT
SE
BAY OF EXPLOITS
0
5km
49°15'
49°15'
55°30'
55°05'
SILURIAN AND ORDOVICIAN
Ashgill - Llandovery
8 Botwood Group
Ashgill
7 Point Leamington Greywacke (includes Goldson Conglomerate)
Caradoc
6 Lawrence Harbour Shale
Llanvirn - Llandeilo
5 Exploits Group
ORDOVICIAN OR EARLIER
4 Wild Bight Group
3 Cottrells Cove Group
2 South Lake Igneous Complex
1 Moretons Harbour Group

Figure 1. *Regional geology of the New Bay area. Simplified from Open File (Nfld) Map 90-124. Formations and subunits discussed in the text are undivided in Figure 1 (1:250,000 scale) but are separated on Map 90-124 (1:50,000 scale).*

mudstone, and felsic agglomerate or tuff are subordinate, they alone permit field-based lithostratigraphic subdivision of Units 5 to 8.

The order of superposition of Units 5 to 7, discernible from locally preserved lithostratigraphic contacts, corroborates their biostratigraphic age assignments. Most or all of Unit 5 corresponds to the Exploits Group of recent workers (e.g., Kean *et al.*, 1981). A sparse fauna collected from the upper part of the group in the New Bay area may indicate a Llanvirn–Llandeilo age (S.H. Williams, personal communication, 1990). Rocks included in Unit 5 in the extreme northwest and southeast of its outcrop area (Figure 1) may be more appropriately assigned to the Ordovician and earlier Wild Bight Group and the Cambro-Ordovician Dunnage Melange, respectively (e.g., Williams, 1962).

The most diagnostic and laterally persistant unit in the New Bay area is Unit 6, the Lawrence Harbour Shale, which is observed to conformably overlie Unit 5. Although the focus of considerable structural disruption, it probably originally formed as an anomalously thin unit ranging in age from earliest to latest Caradoc (Williams, *in press*). The Lawrence Harbour Shale has been correlated across the Atlantic Ocean with the strongly condensed Moffat Shale (Helwig, 1967), a major decollement horizon in the Southern Uplands of Scotland.

Conformably overlying Unit 6 in the New Bay area is the Point Leamington Greywacke, bearing Ashgillian graptolites (Williams, *in press*), and the succeeding Goldson Conglomerate, containing Ashgillian limestone clasts (F.L.C. O'Brien, personal communication, 1990). Facies of the Goldson Conglomerate are complexly interstratified with facies of the Point Leamington Greywacke; both comprise Unit 7 in Figure 1. Unit 8 is confined to the western part of the Bay of Exploits, has unknown stratigraphic relations with other units of overlapping or older age, and is tentatively assigned to the Ashgill–Llandovery portion of the Botwood Group (cf. Williams, 1962, 1972; Figure 1).

Throughout the New Bay area, Units 6 to 8 are confined to regional fault-bounded basins. Such basins are generally coincident with early formed, large-scale, structural depressions and many of the bordering faults simply define outcrop boundaries. However, in some localities, Units 6 and 7 display primary stratigraphic relationships at or near the margins of these structural basins. Furthermore, systematic variations in the stratigraphic thickness and relative proportion of component units occur along the margins of the basins as they narrow toward structural culminations. Therefore, as a generalization, basin-margin faults bound sedimentological depocentres as well as structural basins.

LITHOLOGY AND STRATIGRAPHY

MORETONS HARBOUR GROUP (UNIT 1)

In the New Bay area, the Moretons Harbour Group consists of two conformable formations, the older Sweeny Island Formation and the younger Western Head Formation (Dean, 1977). The Sweeny Island Formation is made up of coarse-grained, porphyritic, mafic lava flows as well as localized zones of sheeted dykes separating narrow screens of lava. In ascending order, the Western Head Formation is composed of a lower subunit of mafic agglomerate and pillow breccia, an intermediate subunit of spectacular mafic pillow lava, and an upper subunit of grey chert and siliceous argillite (O'Brien, 1990). The younger formation appears not to contain the abundant swarms of sheeted diabase characteristic of the older formation; however, the Western Head Formation is host to a variety of multiple, mafic to intermediate, minor intrusions.

Neither the stratigraphic base nor the stratigraphic top of the Moretons Harbour Group is exposed in the New Bay area. Its stratigraphic relations to younger units are unknown, unless the Western Head Formation is partly or wholly the equivalent of the Fortune Harbour Formation of the Cottrells Cove Group. If this equivalency is true, then a small amount of thrust displacement has occurred on the Chanceport Fault of Dean and Strong (1977). Although the lower and upper subunits of the Western Head Formation are restricted to a small area in the extreme southwest of the Unit 1 outcrop, they probably indicate that the intermediate subunit of pillow lava has a highly variable thickness.

SOUTH LAKE IGNEOUS COMPLEX (UNIT 2)

The oldest part of the South Lake Igneous Complex is composed of layered gabbros and pyroxenites, which are commonly amphibolitized or chloritized and intruded by diabase dykes. Younger elements of the complex include trondhjemite and granodiorite (Lorenz and Fountain, 1982). Although most of the external boundaries of the complex are faults that are regionally focussed in the Lawrence Harbour Shale and upper Wild Bight Group (O'Brien, 1990; Figure 1), Dean (1977) reports intrusive contacts between granodiorite and Wild Bight country rocks in several localities. The only stratigraphic constraint on the South Lake Igneous Complex and the Wild Bight Group in the New Bay area is the observation of probable detrital clasts of both units in Ashgillian (Unit 7) strata.

COTTRELLS COVE GROUP (UNIT 3)

The main tract of the Cottrells Cove Group corresponds with the distribution of Unit 3, although recognizable tectonic slivers of this group occur, with or without associated melange belts, in the major mylonite zone to the south. The Cottrells Cove Group contains two formations, the older Fortune Harbour Formation and the younger Moores Cove Formation. In ascending order, the Fortune Harbour Formation is made up of a lower subunit of mafic agglomerate and pillow breccia, an intermediate subunit of spectacular pillow lava, and an upper subunit of felsic tuff and agglomerate interbedded with grey and red chert and siliceous argillite (O'Brien, 1990). The Moores Cove Formation is composed of distinctly weathered, ferruginous and calcareous, feldspathic and lithic wacke interbedded with variable amounts of grey argillite. Taken regionally and as a whole, the formation is thick-bedded at its stratigraphic base and becomes thin-bedded toward the top of the exposed succession.

Neither the stratigraphic base nor the stratigraphic top of the Cottrells Cove Group is exposed. As originally defined, the Moores Cove Formation represented the lowest formation of the north-facing, Silurian Cottrells Cove Group (Dean, 1977) and was held to have been originally stratigraphically continuous (Kean *et al.*, 1981) with Upper Ordovician wacke and olistostromal melange (Unit 7). In tectonic terms, this basal formation of volcanogenic flysch was purported to separate an overlying, post-Ashgillian, island-arc volcanic sequence from an underlying, pre-Caradocian, island-arc volcanic sequence floored by ophiolitic basement (Dean, 1978).

Re-assigning the Moores Cove Formation to a position stratigraphically above the Fortune Harbour Formation (O'Brien, 1990) has important paleogeographic implications for the evolutionary development of the Cottrells Cove Group. Although most commonly faulted, the contact between the Fortune Harbour and Moores Cove formations is observed to be stratigraphically gradational. Primary lateral changes in the rock types are the likely cause of the present distribution of subunits. As a result, mafic volcanic and (variably thin) felsic volcanic rocks occur chiefly in the north of the Cottrells Cove Group, whereas mafic volcanic and (variably thick) sedimentary rocks are present mostly in its southerly outcrop. The intermediate subunit of pillow lava in the Fortune Harbour Formation is widespread in the northwestern part of the area near the northern fault boundary of Unit 3. It is also found as small tectonic inliers in the Moores Cove Formation, especially in the southeastern part of Unit 3 near its southern fault boundary. However, the outcrop pattern of this pillow lava subunit suggests that, in the northwestern exposures of the Fortune Harbour Formation, it is not appreciably thick. Based upon similar arguments, the Moores Cove Formation appears to obtain substantial thicknesses only along the southeastern flank of the Cottrells Cove Group.

WILD BIGHT GROUP (UNIT 4)

In the New Bay area, only a small proportion of the Wild Bight Group is represented by Unit 4 in Figure 1. Dean (1977) correlated most of the rocks included in Unit 4 with the Pennys Brook Formation, a mappable unit that he considered as the uppermost formation of the Wild Bight Group.

Unit 4 is composed of two subunits (O'Brien, 1990); one chiefly of volcanic rocks and the other largely of sedimentary rocks. Mafic agglomerate, pillow breccia and pillow lava form the older subunit. The younger subunit contains distinctively green, siliceous argillite interbedded with tuffaceous sandstone and ferruginous wacke. Grey and red parallel-laminated cherts are also present.

Neither the stratigraphic base nor the stratigraphic top of the Wild Bight Group is exposed in the New Bay area. The outcrop of the mafic volcanic subunit of Unit 4 is restricted to the extreme west of the area and is areally insignificant in comparison to the sedimentary subunit.

EXPLOITS GROUP (UNIT 5)

The New Bay area contains the type area of what recent workers refer to as the Exploits Group (Dean, 1977). Unit 5 generally corresponds with the Exploits Group as compiled by Kean *et al.* (1981) and, as such, it is the most widely distributed unit in the region (Figure 1). Although Helwig (1967) employed the term Exploits Group to include Units 5 to 7, he nevertheless, originally separated most of Unit 5 into four conformable units of formational rank. In ascending order, these regionally mappable yet locally discontinuous units are the Tea Arm Volcanics, the Saunders Cove Formation, the New Bay Formation and the Lawrence Head Volcanics.

The Tea Arm Volcanics consists of a lower subunit of spectacular pillow lava associated with abundant mafic dykes and sills, an intermediate subunit of felsic tuff and agglomerate, and an upper subunit of mafic agglomerate, pillow breccia and pillow lava along with minor interbeds of feldspathic wacke and laminated argillite (O'Brien, 1990). The Saunders Cove Formation sharply overlies the Tea Arm Volcanics and contains red chert, interbedded red and green, siliceous argillite, feldspathic wacke and minor conglomerate. Gradationally overlying the Saunders Cove Formation is the older of two, stratigraphically gradational subunits of the New Bay Formation (O'Brien, 1990). It is generally composed of interbedded, grey shale and grey sandstone, although conglomeratic wacke is also common in the lower part of the subunit. The younger subunit of the New Bay Formation is made up of feldspathic wacke and graded, boulder to cobble conglomerate at its base and contains increasing amounts of grey argillite near its top. In some but not all locations, the spectacular pillow lava and pillow breccia of the Lawrence Head Volcanics sharply overlie the New Bay Formation.

In the New Bay area, the stratigraphic base of the Exploits Group is not exposed; however, its stratigraphic top is observable in the eastern part of the region beneath the Lawrence Harbour Shale (Figure 1). Some of the sedimentary rocks in the Wild Bight Group (Unit 4) are identical to fossil-bearing strata in the uppermost Exploits Group and, in terms of lithofacies, are similar to parts of the Saunders Cove and New Bay formations. Therefore, the Exploits and Wild Bight groups may be partially equivalent and conceivably be Exploits Subzone correlatives. However, considering the overall stratigraphy and lithology of the Exploits Group, the strongest case for its correlation could be made with the Cottrells Cove Group in the Notre Dame Subzone immediately north of the Red Indian Line structural zone. Clearly, correlation of rock units in the Dunnage Zone cannot be based on stratigraphy and lithology alone (e.g., Heyl, 1936) and must await the integration of petrochemical, paleontological, geochronological and paleomagnetic data.

Throughout the New Bay area, a thin subunit of graptolite-bearing, ferruginous chert and feldspathic wacke lies conformably beneath the Lawrence Harbour Shale. It displays complex facies relations with mappable units of Llanvirn–Llandeilo limestone in the Bay of Exploits region. This regionally extensive subunit rests, in different localities, conformably above the lower and upper Tea Arm Volcanics, the upper New Bay Formation and the top of the Lawrence Harbour Volcanics. It appears to pass laterally into the Saunders Cove Formation and, possibly, the intermediate subunit of felsic volcanic rocks in the Tea Arm Volcanics. The maximum, total-combined, stratigraphic thickness of Exploits Group formations occurs in the east of the New Bay area, where at least 3.5 km of strata underlies the distinctive subunit of ferruginous chert and feldspathic wacke. Toward the west, the Exploits Group appears to thin dramatically beneath its uppermost graptolitic subunit. The lack of a surface of erosional unconformity beneath this subunit suggests that the volcano-sedimentary constituents of the Exploits Group basin were already exposed in variably thick, rock belts by Llanvirn–Llandeillo time, long before the initiation of regional deformation.

LAWRENCE HARBOUR SHALE (UNIT 6)

The New Bay area contains the type area and reference section of the Lawrence Harbour Shale (Williams, *in press*). All Unit 6 occurrences in the New Bay area (Figure 1) have been previously correlated with the black shale and cherty black shale sequences at Lawrence Harbour (Helwig, 1967; Dean, 1977).

The Lawrence Harbour Shale contains several distinctive subunits that are present over a large region but are difficult to map individually. In ascending order, they are bioturbated grey chert associated with black argillite laminae, black pyritiferous siltstone having black shale partings, and black carbonaceous shale (O'Brien, 1990). Although the lowest subunit is apparently unfossiliferous and occurs stratigraphically below the first continuous bed of graptolite-bearing (Caradocian) black shale, it is conformable with overlying strata. Most workers consider the laminated grey chert subunit as a part of the Lawrence Harbour Formation and, therefore, it is included in Unit 6 in Figure 1.

In the New Bay area, the stratigraphic top of the Lawrence Harbour Shale is positioned at its gradational contact with the Ashgillian Point Leamington Greywacke (Williams, *in press*). The stratigraphic base of the Lawrence Harbour Shale is placed at its gradational contact with the Llanvirn–Llandeilo subunit of ferruginous chert and feldspathic wacke that occurs at the top of the Exploits Group and possibly the uppermost Wild Bight Group. Despite having conformable lower and upper contacts, it is practical to exclude the Lawrence Harbour Shale and succeeding units from the Exploits Group. This is because biostratigraphically equivalent units of Caradocian black shale comprise an integral part of several groups that are widely dispersed throughout the Exploits Subzone (S.H. Williams, personal communication, 1990).

POINT LEAMINGTON GREYWACKE AND GOLDSON CONGLOMERATE (UNIT 7)

In Figure 1, the Point Leamington Greywacke and the Goldson Conglomerate are grouped together as interstratified units of Ashgillian age (Unit 7). Within the New Bay area, they crop out in two distinct structural basins; one centred around New Bay and the other located in the Bay of Exploits. Whereas the Point Leamington Greywacke is the major constituent of both basins, the Goldson Conglomerate appears to be more extensive in the New Bay basin.

In both the New Bay and Bay of Exploits areas, the Point Leamington Greywacke consists of two subunits (O'Brien, 1990), present in variable proportions in various parts of the basins. The most widespread and volumetrically significant subunit consists of interbedded grey shale and light grey, quartzofeldspathic wacke. It occurs stratigraphically below and, in some parts of the basins, also stratigraphically above the other subunit, which is much more distinctive and faunally diagnostic. Dark-grey carbonaceous shale, light-grey quartzofeldspathic wacke, and olistostromal melange having a black shale matrix comprise the second subunit.

Although there appears to be several, stratigraphically distinct bodies of Goldson Conglomerate, especially in the New Bay basin, each wedge-shape body contains interbedded grey pebbly wacke and graded, boulder to cobble, grey conglomerate (O'Brien, 1990). Mixed extrabasinal and intrabasinal detritus is present in thick polymictic conglomerate horizons. Variably sized, conspicuous clasts of coralline limestone have yielded Ashgillian conodonts (F.L.C. O'Brien, personal communication, 1990) that provide older age limits for the Goldson Conglomerate. In places, grey shale successions separating small tongues of Goldson Conglomerate contain graptolites and illustrate features indicative of turbiditic sedimentation.

Regionally, the Goldson Conglomerate conformably overlies the Point Leamington Greywacke–despite them being complexly interstatified in local parts of the basins. The stratigraphic top of the Goldson Conglomerate is, however, not exposed in the New Bay area. Williams (1962, 1972) placed the Goldson Conglomerate as the basal formation of the Botwood Group, and interpreted this group of Upper Ordovician and Silurian strata as being conformable with Units 5, 6 and 7. Kean *et al.* (1981) removed the Goldson Conglomerate from the Botwood Group but still considered the marine conglomeratic unit to lie stratigraphically beneath the Botwood Group.

BOTWOOD GROUP (UNIT 8)

In the New Bay area, Unit 8 represents a very small tract of Ashgill–Llandovery (W.D. Boyce and S.H. Williams, personal communications, 1990) volcano-sedimentary rocks, which are readily distinguishable from the nearby outcrop of the Ashgillian Point Leamington Greywacke. Accordingly, they are tentatively assigned to the Botwood Group. Several distinctive subunits are exposed on islands in the Bay of Exploits (Figure 1), however, their order of superposition has yet to be determined. Unit 8 includes: a subunit of limy shale, coticule-bearing argillite, calcareous sandstone, siliceous wacke and clastic limestone; a subunit of mafic lava, mafic sills and mafic breccia interbedded with feldspathic wacke and laminated calcareous argillite; and a subunit of polylithic conglomerate and olistostromal melange containing blocks of coralline limestone, green chert and mafic volcanic rocks (O'Brien, 1990).

Neither the stratigraphic base nor the stratigraphic top of Unit 8 is exposed in the New Bay area. The main tract of the Botwood Group, which is largely composed of undated alluvial and deltaic strata in the Lawrenceton and Wigwam formations, occurs much farther southeastward (Williams, 1962). Although shallow-marine Silurian strata (W.D. Boyce, personal communication, 1990) occur near the estuary of the Bay of Exploits and are included in the Botwood Group, they have unknown relations with the deep marine strata of Unit 8 or the terrestrial strata of the Lawrenceton and Wigwam formations. Regional overstep may have occurred during Botwood Group deposition (Williams, 1972) from a depocentre sited near the western part of the Bay of Exploits toward a starved arch located east of the bay.

STRUCTURE

The New Bay area lies within a regional oroclinal flexure in north-central Newfoundland defined, in part, by northeast- and northwest-trending segments of the Red Indian Line structural zone. Major structural features, which outline this oroflex, include a first-order mylonite zone and melange belt, and second-order folds and thrust faults that are themselves regionally extensive (Figure 1). Third-order transcurrent faults trend consistently northeastward across the oroflex.

FOLDS AND FAULTS

Regional bulk-strain patterns were established early during the development of first-generation folds and faults. Areas affected by small total-strain are typified by periclinal anticlinoria and synclinoria about which stratigraphic successions are continuously disposed. Major periclinal folds are located in regionally developed, structural domains characterized by either dominantly northwest- or dominantly northeast-trending, first-generation structures (Figure 1). For the most part, anticlinoria and synclinoria are generally open and gently plunging. Less commonly, areas of negligibly strained strata are also encountered in the hinge zones of steeply plunging, major folds. In such localities, first-generation minor folds, whose axes trend both northeast and northwest, mutually overprint each other.

Most of the major fault zones in the New Bay area formed as high-angle thrusts, which placed older rocks over younger rocks in most, although not all, locations (Figure 2). Approaching these thrusts, first-generation folds (1) become tighter as they concomitantly increase their pitch on axial surfaces, (2) develop a stronger sense of asymmetry (vergence) and (3) become overturned toward the general direction of hanging-wall transport. Although rocks in the hanging walls and footwalls behaved ductilely and show an increase in strain toward thrusts, the sharply defined fault planes are the sites of narrow zones of cataclasis.

In many locations, observable thrust planes dip subvertically. Where fault planes are mesoscopically folded in individual exposures, the steep dip of thrusts is most readily explained by the effect of subsequent deformation (e.g., Dean and Strong, 1977). However, regionally, dips of thrust faults and associated platey zones vary in accord with systematic differences in axial-surface inclinations of the major folds in the low-strain regions. As thrust-zone dips change from steep to gentle along strike, regional overfolds begin to predominate over regional upright folds, although the fold plunge generally remains shallow. Such changes are likely to be primary, as secondary structures are rare in the negligibly strained, simply folded regions. In Figure 1, barbs are drawn on what is deemed the upthrown sides of thrust faults based on regional variations in the vergence and plunge of first-generation folds.

In the New Bay area, first-generation folds and thrusts do not display a regionally dominant direction of axial-surface inclination or fault polarity, respectively. This is particularly evident around the periphery of regions of small bulk strain. Synfolding thrusts on the limbs of anticlinal periclines or domes generally dip inward, converging downward in the direction of the axial traces of regional anticlinoria (Figure 2). Similarly, synfolding thrusts on the limbs of synclinal periclines or basins generally dip outward, diverging downward in a direction away from the axial traces of regional synclinoria. This is consistent with the observation of relatively narrow tracts of inverted strata on periclinal flanks, adjacent to curviplanar thrusts and smaller scale, overturned folds. In the westernmost part of the Exploits Subzone, it appears that thrust-bounded lithostratigraphic assemblages were not transported in a preferred tectonic direction, either toward or away from the Salinic–Acadian hinterland located farther east. This feature, in addition to the lack of any evidence favouring sequential thrusting and back thrusting, supports the interpretation that first-generation structures are mutually interfering and belong to a conjugate system of folds and thrusts.

Whereas subsequent semi-brittle deformation is widespread and witnessed by dextral transcurrent faults and related megakinks of regional periclines and thrusts (Figure 1), ductile deformation postdating first-generation structures is focussed along basin-margin fault zones. In the New Bay area, northeast- and northwest-trending folds of thrust faults are present on various scales; most of those depicted on Figure 2 are shown in oblique section rather than in fold profile. As a regional generalization, where such folds are open to close and gently to moderately, doubly plunging, they commonly display sinistral vergence. However, where thrust planes and imbricate thrust sheets are tightly to isoclinally folded about variably, but generally steeply plunging secondary structures, they illustrate dextral vergence.

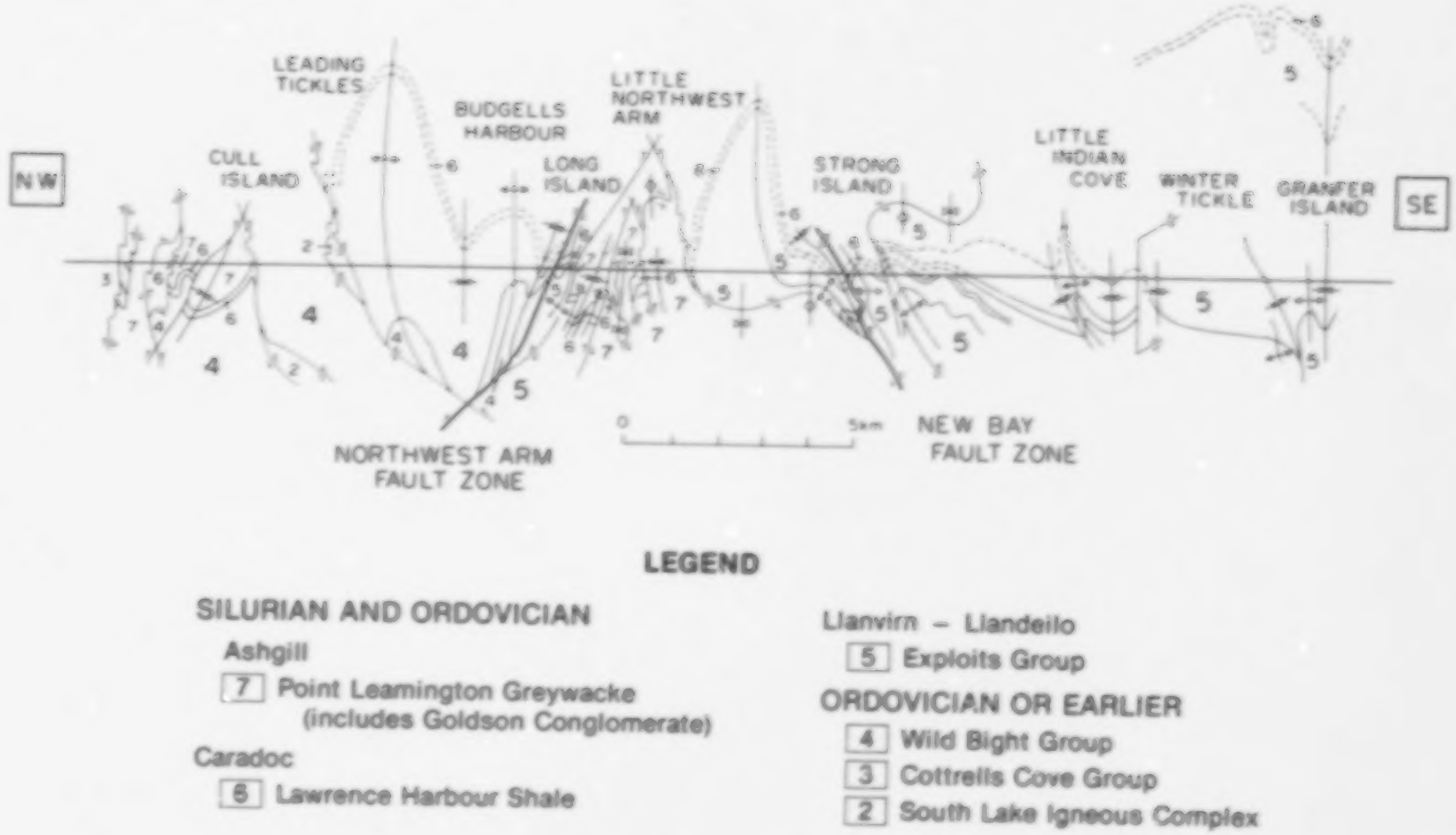
NW
SE
CULL ISLAND
LEADING TICKLES
BUDGELLS HARBOUR
LONG ISLAND
LITTLE NORTHWEST ARM
STRONG ISLAND
LITTLE INDIAN COVE
WINTER TICKLE
GRANFER ISLAND
NORTHWEST ARM FAULT ZONE
NEW BAY FAULT ZONE
0
5km
LEGEND
SILURIAN AND ORDOVICIAN
Ashgill
7 Point Leamington Greywacke (includes Goldson Conglomerate)
Caradoc
6 Lawrence Harbour Shale
Llanvirn – Llandeilo
5 Exploits Group
ORDOVICIAN OR EARLIER
4 Wild Bight Group
3 Cottrells Cove Group
2 South Lake Igneous Complex

Figure 2. *Representative geological cross-section of the New Bay area. Form lines are coincident with the boundaries of formations and subunits comprising some of the major groups and units. Folds and faults are indicated by symbols. Second-generation folds distinguished from first-generation folds by open arrow heads. Line of section indicated on Figure 1.*

Second-generation folds commonly display an opposing sense-of-vergence (shear sense) than first-generation folds. Consequently, near one boundary of a thrust sheet, dextral folds overprint sinistral folds whereas, near its other boundary, sinistral folds overprint dextral folds. A complimentary observation is that second-generation structures typically face either downward or sideways on both margins of thrust sheets. It appears that, with progressive deformation, the surfaces of thrusts replaced the surfaces of beds as the principal planes of anisotropy. As a result, first-generation synclinoria bounded by conjugate divergent thrusts evolve into second-generation antiformal domes outlined by the early formed faults (Figure 2).

In areas of large total strain, folded thrust sheets outline vertically elongated, dome-and-basin shapes or 'doubly hooked- to eye-shaped' outcrop patterns. Because it is a fault plane rather than a stratigraphic boundary which is folded, such shapes and patterns are unlikely to have been produced by the interference of first- and second-generation folds. Alternatively, if they are sheath folds of thrusts, then the extension direction is presumably subvertical. This would imply that the secondary structures form in response to ductile dip-slip movements and localized shearing in the basin-margin fault zones.

FOLIATIONS

A widespread slaty cleavage defining regional cleavage arcs formed concomitantly with first-generation structures. This foliation developed in a very complex fashion independently from both associated folds and thrusts (e.g., Blewett and Pickering, 1988; Lafrance *et al.*, 1989). Variably spaced, crenulation cleavage is associated with the second-generation, curvilinear folds as well as the later megakinks and transcurrent faults.

Approaching the boundaries of thrust sheets well south or north of the Red Indian Line, a variably pervasive slaty cleavage intensifies and lies parallel to bedding and thrusts in platey zones, which are up to 50 m thick. Highly attenuated, sedimentary and volcanic rocks in these platey zones are reddened in places, presumably as a result of iron oxidization. Laterally discontinuous layers of mylonite and cataclasite, from a centimetre to a decimetre in thickness, occur concordantly within the platey zones.

Most of the bifurcating thrusts in the Exploits and Notre Dame subzones coalesce in the tightly braided mylonite zone marking the Red Indian Line (Figure 1). Over its 2 to 3 km width, the majority of rocks are platey or mylonitic. However, imbricated with these rocks, are relatively small, discontinuous sheets of scaly foliated melange (Cowan, 1985; Moore *et al.*, 1986).

Characteristic features of these melange belts are: (1) that the constituent, unstratified, block-in-matrix rocks are progressively deformed and restricted to the Red Indian Line structural zone, (2) that many of the inclusions or blocks can be identified in unbroken formations or nondisrupted sequences in the Cottrells Cove and Exploits groups, (3) that rocks of known Ashgill and Llandovery age, although present as clasts in olistostromes of demonstrable sedimentary origin, are not observed to pass gradationally into scaly foliated, chaotic melange, (4) that the dark scaly clays in the matrix were produced by brittle or cataclastic deformation, which either predated or accompanied regional ductile deformation, and (5) that melange units are deformed by thrusts, folds and crenulation cleavages that affect Ashgill and Llandovery strata.

MAGMATISM

Most if not all of the plutonic rocks in the New Bay area can be regarded as minor intrusions that range as widely in age as they do in areal extent. Since very few are regionally mappable, they are not shown in Figures 1 or 2. The greatest compositional variety and largest abundance of minor intrusions occur in Early Ordovician or older rocks. Although mafic dykes and sills of synvolcanic and/or syndiagenetic origin occur in the Exploits, Wild Bight, Cottrells Cove and Moretons Harbour groups, they are not numerous and do not appear to have any regional pattern of distribution. In contrast, most plutonic and associated hypabyssal rocks in the New Bay area were emplaced during or after episodes of regional deformation. Suites of undated, minor intrusions are most commonly located within regional anticlinoria or near major thrust faults, both of which are situated along the margins of structural or sedimentological basins (Figure 2).

In the New Bay area, the only dated plutonic and hypabyssal rocks are Mesozoic in age and comprise a part of the Budgells Harbour Gabbro (Strong and Harris, 1974). The undated Long Island Granodiorite, which crops out near the eastern margin of the map area, appears to truncate most of the structures in the Red Indian Line structural zone and is interpreted to thermally metamorphose strata that are as young as Llandovery in age.

Earlier plutonic and hypabyssal rocks include multiple sheets of gabbro, diorite and diabase as well as composite intrusions of quartz–feldspar porphyry and diabase. Commonly folded and locally foliated, they occur in both the Notre Dame and Exploits subzones and are the most widespread minor intrusions in the New Bay area (O'Brien, 1990).

Where the gabbro–diorite sheets exceed 100 m in thickness, they commonly produce spotted hornfels in adjacent country rocks. In some localities, these hornfelses contain biotite porphyroblasts that overprint the regional slaty cleavage. In the dyke swarm of the New Bay Fault Zone, gabbro–diorite sheets posttectonically intrude older suites of variably mylonitized, mafic intrusions hosted by highly deformed, Caradocian slate. In one of the imbricate thrust sheets of the New Bay Fault Zone, mafic sills yielding geopetal evidence from graded cumulate bands were overfolded and inverted prior to being re-injected by diabase.

The strongest evidence for syntectonic intrusion of this regional swarm of gabbro–diorite sheets comes from their dynamic relationships to mesoscopic and map-scale, folds and faults. In some areas, first-generation folds defined by bedding or regional stratigraphy are also outlined by gabbro–diorite sills. In other localities, gabbro–diorite dykes crosscut strata-defined or older sill-defined, tectonic folds. However, these same dykes are also observed to outline variably plunging, first-generation folds, which are overprinted or transected by regional slaty cleavage. Such intrusion-defined folds commonly have a larger wavelength and amplitude than those defined by bedding. Emplaced parallel, perpendicular and tangential to foliations, fold-axial surfaces or thrust faults, these minor intrusions display characteristic T- and Y-shaped abutments as well as mutually crosscutting margins.

Notable features of the gabbro–diorite sheets are the thickness variations they display and the positions they occupy in regional scale structures (O'Brien, 1990). Relatively thick, large and solitary intrusions are located in the crestal regions of gently plunging, W- and M-shaped, chevron folds typified by small bulk strains. Relatively thin, small and discontinuous intrusions occur on the limbs of steeply plunging, isoclinal folds or the hanging walls of high-angle thrust faults, both characterized by large bulk strains. Apparently, this distribution is not caused by variations in the degree of tectonic attenuation of the minor intrusions. Rather, regional bulk-strain patterns were already largely in existance prior to magma emplacement and were important parameters in establishing the selective modes of dilatation discussed above. Such processes were also operative, at a later date, when a dyke suite of intermediate composition, developed in equal proportions in early and Late Ordovician basins, was intruded parallel to and preferentially along east-northeast-trending transcurrent faults.

In summary, syntectonic intrusive suites were preferentially emplaced into major ductile fault zones near dilatant structures such as thrust-bounded anticlines or transcurrent faults. In places, they may have utilized the same conduits as the synvolcanic dykes that feed the dominantly volcanic parts of the pre-Caradocian successions.

MINERALIZATION

Disseminated and vein-hosted chalcopyrite mineralization occurs locally within variably pyritized and silicified units of mafic volcanic rocks in the Exploits, Wild Bight and Cottrells Cove groups. In many locations, where the alteration process has completely replaced the original mineralogy of the mafic lava, pseudomorphs of negligiably strained pillows are preserved. Relatively thin, discontinuous units of felsic pyroclastic rocks are commonly associated with the mineralized pillow lava units, although the former are generally much less altered. Elsewhere, at unambiguous stratigraphic contacts, these pillow lava units directly underlie the felsic volcanic rocks. Regionally, the alteration zones follow the folded boundary between the mafic and felsic units suggesting that the mineralization is essentially in the form of stratabound stockworks.

In several localities in the New Bay area, gabbro–diorite sheet intrusions host vein arrays with bilateral, pyrite- and iron carbonate-rich, alteration zones. The adjacent hornfelses of the Exploits and Botwood groups are locally altered, especially where ductility contrasts between country rock and minor intrusion are insignificant. In some intrusive bodies, carbonate alteration increases concomitantly with foliation development. Periods of deformation and alteration are bracketed by various phases of these multiple syntectonic intrusions. Fault zones that yield evidence of a protracted history of mafic intrusion followed by leucogranite or quartz feldspar porphyry are particularly good targets for gold exploration, especially in the Exploits Subzone.

DISCUSSION AND CONCLUSIONS

Submarine mafic lavas, with or without contemporaneous felsic volcanic rocks or thin limestones, are present at several stratigraphic intervals in Early Ordovician and Early Silurian rock groups, but are conspicuously absent from marine units of intermediate age. The lack of Late Ordovician deep-sea volcanism, the increasing carbonate content of Ashgillian strata, and the rise of Caradocian sea level throughout the Exploits Subzone presumably signify a major shift in the paleotectonic and/or paleolatitudinal setting of Early Silurian volcanic islands or seamounts relative to those of Early Ordovician or older age (e.g., van der Pluijm and van Staal, 1988; van der Pluijm *et al.*, 1990). At some time after the cessation of Taconian (mid-Caradoc) obduction along the western margin of the Notre Dame Subzone, there seems to have been significant paleogeographic reconstruction of at least some of the Early Ordovician oceanic basins in the Dunnage Zone (e.g., Neuman, 1984; van Staal *et al.*, 1990). Early Silurian volcanism and sedimentation in remnant oceanic basins of the Dunnage Zone was contemporaneous with this shift in tectonic regime, which caused the bulk of orogen-derived sediment to accumulate east, rather than west, of the sutured Taconian magmatic arc (e.g., Nelson and Casey, 1979; Bourque, 1989).

Discrete unconformity-bounded sequences of Ordovician or Silurian strata are absent in the New Bay area. This, together with the lack of evidence of demonstrable, pre-Llandovery, regional deformation of the basin-fills, suggests that tectonic and/or thermal subsidence were not triggered by the partial closure and sequential inversion of Ordovician and Silurian basins. Nevertheless, a critical feature of the New Bay area is that the depocentres of Early Ordovician, Late Ordovician and Early Silurian basins are not regionally coincident. Although the regional cause of the shift of depocentres is unknown, this phenomenon seemingly indicates that subsidence and deposition were episodic and unsteady rather than being continuous and site-specific. It may be that the relative disposition of depocentres was controlled by the variable location of a broad regional syndepositional bulge (e.g., the outer arc of a piggyback basin) and its consequential effect on the lateral migration of Ordovician and Silurian basins.

The Late Ordovician basin near New Bay appears to have been sited on an arch that was starved of Early Ordovician deposits (Figure 2). Early Silurian volcano-sedimentary rocks are interpretated to have originally covered only the eastern extremity of the New Bay area. A deep marine basin of Ashgill–Llandovery age, unlinked to the Late Ordovician basin in New Bay, is thought to have developed along the southeastern flank of a probable Late Ordovician arch located in the western part of the Bay of Exploits.

In several locations in the New Bay area, slump-folded wacke and iron-rich chert of probable Early Ordovician age display complex stratigraphic relationships with submarine volcanic rocks, which locally host cupriferous stockworks and silicic alteration zones. Pre-Caradocian units in the sedimentary-dominated and volcanic-dominated belts intertongue along and across strike in the vicinity of some of the major fault zones. There, such units are seen to be affected by abrupt facies changes, thickness variations and periodic emergence above carbonate compensation depths.

Certain parts of the New Bay area are possibly underlain by a condensed Llanvirn–Llandeillo succession. These areas may have been starved of the sedimentary and volcanic deposits that accumulated by relatively accelerated modes of deposition in adjacent parts of the region. In the lower parts of the Exploits and Cottrells Cove groups, thick sequences of pillow lava are capped by thin discontinuous horizons of felsic tuff and associated chert, which pass laterally into proximal, feldspathic and lithic wacke. The positions of the felsic pyroclastic domes in these volcanic belts relative to the volcanogenic wacke and plutonic boulder conglomerate of the adjoining sedimentary belts may have important implications for the regional setting of base-metal mineralization in the area. The regional horizontal and vertical distribution of members of the Exploits Group, taken together with the variable offset of its subunits relative to that of the overlying Lawrence Harbour Shale, possibly indicates the presence of an Early Ordovician fault scarp within the New Bay Fault Zone (Figure 2).

Cyclical, localized uplift may have occurred near tectonic hinge lines situated along basin margins, themselves isostatically controlled by synsedimentary and synvolcanic faults. Pre-Caradocian fault zones antedate late Taconic uplift (*sensu* Nelson, 1981) but they may herald the Late Ordovician–Early Silurian shift in tectonic regime. As ancestral faults, they may have been reactivated during the formation of Ashgillian debris flows and arc-derived conglomeratic flysch. Subsequently, tectonic structures and magmas of post-Llandovery age appear to have been focussed along these basin-margin faults.

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REFERENCES

Blewett, R.S.
1989: Melange development along the Luke's Arm–Sop's Head Fault (Red Indian Line): a major lineament controlling deformation in Notre Dame Bay, north-central Newfoundland, Canada. Geological Association of Canada–Mineralogical Association of Canada Joint Annual Meeting, Montreal, Program with Abstracts, Volume 14, page A10.

Blewett, R.S. and Pickering, K.T.
1988: Sinistral shear during Acadian deformation in north-central Newfoundland, based on transecting cleavage. Journal of Structural Geology, Volume 10, number 9, pages 125-127.

Bostock, H.H.
1988: Geology and petrochemistry of the Ordovician volcano-plutonic Robert's Arm Group, Notre Dame Bay, Newfoundland. Geological Survey of Canada, Bulletin 369, 84 pages.

Bourque, P.A.
1989: Upper Ordovician to Middle Devonian rocks of Gaspe Peninsula. *In* Sedimentology, Paleoenvironments and Paleogeography of the Taconian to Acadian Rock Sequence of Gaspe Peninsula. *Edited by* P.A. Bourque, R. Hesse and B. Rust. Geological Association of Canada–Mineralogical Association of Canada, Field Trip Guide Book B8, pages 1-55.

Cowan, D.S.
1985: Structural styles in Mesozoic and Cenozoic melanges in the western Cordillera of North America. Geological Society of America, Volume 96, pages 451-462.

Dean, P.L.
1977: A report of the geology and metallogeny of the Notre Dame Bay area, to accompany metallogenic maps 12H/1, 8, 9, and 2E/3, 4, 5, 6, 7, 9, 10, 11 and 12. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-10, 17 pages.

1978: The volcanic stratigraphy and metallogeny of Notre Dame Bay. Memorial University of Newfoundland, Geology Report 7, 204 pages.

Dean, P.L. and Strong, D.F.
1977: Folded thrust folds in Notre Dame Bay, central Newfoundland. American Journal of Science, Volume 277, number 2, pages 97-108.

Dunning, G.R., Kean, B.F., Thurlow, J.G. and Swinden, H.S.
1987: Geochronology of the Buchans, Roberts Arm and Victoria Lake groups and Mansfield Cove Complex, Newfoundland. Canadian Journal of Earth Sciences, Volume 24, pages 1175-1184.

Helwig, J.A.
1967: Stratigraphy and structural history of the New Bay area, north-central Newfoundland. Unpublished Ph.D. thesis, Columbia University, New York, 211 pages.

Heyl, G.R.
1936: Geology and mineral deposits of the Bay of Exploits area. Newfoundland Geological Survey, Bulletin 4, 66 pages.

Horne, G.S. and Helwig, J.A.
1969: Ordovician stratigraphy of Notre Dame Bay. *In* North Atlantic Geology and Continental Drift. *Edited by* M. Kay. American Association of Petroleum Geologists, Memoir 12, pages 388-407.

Kean, B.F., Dean, P.L. and Strong, D.F.
1981: Regional geology of the Central Volcanic Belt of Newfoundland. *In* The Buchans Orebodies: Fifty Years of Geology and Mining. *Edited by* E.A. Swanson, J.G. Thurlow and D.F. Strong. Geological Association of Canada, Special Paper 22, pages 65-78.

Keen, C.E., Keen, M.J., Nichols, B., Reid, I., Stockmal, G.S., Colman-Sadd, S.P., O'Brien, S.J., Miller, H., Quinlan, G., Williams, H. and Wright, J.
1986: A deep seismic reflection profile across the northern Appalachians. Geology, Volume 14, pages 141-145.

Lafrance, B., Williams, P.F. and Elliot, C.G.
1989: Sinistral shear during Acadian deformation in north-central Newfoundland, based on transecting cleavage: Discussion. Journal of Structural Geology, Volume 11, number 3, pages 365-368.

Lorenz, B.E. and Fountain, J.C.
1982: The South Lake Igneous Complex, Newfoundland: a marginal basin–island arc association. Canadian Journal of Earth Sciences, Volume 19, pages 490-503.

Marillier, F., Keen, C.E., Stockmal, G.S., Quinlan, G., Williams, H. and Colman-Sadd, S.P.
1989: Crustal structure and surface zonation of the Canadian Appalachians: implications of deep seismic reflection data. Canadian Journal of Earth Sciences, Volume 26, pages 305-321.

Moore, J.C., Roeske, S., Lundberg, N., Schoonmaker, J., Cowan, D.S., Gonzales, E. and Lucas, S.E.
1986: Scaly fabrics from Deep Sea Drilling Project cores from forearcs. *In* Structural Fabric in Deep Sea Drilling Project Cores From Forearcs. *Edited by* J.C. Casey. Geological Society of America, Memoir 166, pages 55-73.

Nelson, K.D.
1981: Melange development in the Boones Point Complex, north-central Newfoundland. Canadian Journal of Earth Sciences, Volume 18, pages 433-442.

Nelson, K.D. and Casey, J.D.
1979: Ophiolitic detritus in the Upper Ordovician flysch of Notre Dame Bay and its bearing on the tectonic evolution of western Newfoundland. Geology, Volume 7, pages 27-31.

Neuman, R.B.
1984: Geology and paleobiology of islands in the Ordovician Iapetus Ocean: Review and implications. Geological Society of America Bulletin, Volume 95, pages 1188-1201.

O'Brien, B.H.
1990: Geology of the New Bay area (parts of 2E/6 and 2E/11), Notre Dame Bay, Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File Map 90-124, scale 1:50,000.

Strong, D.F. and Harris, A.
1974: The petrology of Mesozoic alkaline intrusives of central Newfoundland. Canadian Journal of Earth Sciences, Volume 11, pages 1208-1219.

Swinden, H.S., Kean, B.F. and Dunning, G.R.
1988: Geological and paleotectonic settings of volcanogenic sulphide mineralization in central Newfoundland. *In* Volcanogenic Sulphide Districts of Central Newfoundland. *Edited by* H.S. Swinden and B.F. Kean. Mineral Deposits Division, Geological Association of Canada, 260 pages.

van der Pluijm, B.A., Johnson, R.J.E. and van der Voo, R.
1990: Paleogeography and tectonic history of the northern Appalachians. Geological Society of America, Northeastern Section, Annual Meeting, Program with Abstracts, Volume 22, number 2, page 76.

van der Pluijm, B.A. and van Staal, C.R.
1988: Characteristics and evolution of the Central Mobile Belt, Canadian Appalachians. Journal of Geology, Volume 96, pages 535-548.

van Staal, C.R., Ravenhurst, C.E., Winchester, J.A., Roddick, J.C. and Langton, J.P.
1990: Post-Taconic blueschist suture in the northern Appalachians of northern New Brunswick, Canada. Geology, Volume 18, pages 1073-1077.

Williams, H.
1962: Botwood (west-half) map area. Geological Survey of Canada, Paper 62-9, scale 1:250,000.

1972: Stratigraphy of the Botwood map area, northeastern Newfoundland. Geological Survey of Canada, Open File 113, 103 pages.

Williams, H., Colman-Sadd, S.P. and Swinden, H.S.
1988: Tectonic-stratigraphic subdivisions of central Newfoundland. *In* Current Research, Part B, Geological Survey of Canada, Paper 88-1B, pages 91-98.

Williams, S.H.
In press: Stratigraphy and graptolites of the upper Ordovician Point Leamington Formation, central Newfoundland. Canadian Journal of Earth Sciences.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 167-178

GEOLOGY OF THE SOUTHEASTERN PART OF THE GANDER LAKE MAP AREA (NTS 2D/15) AND THE SOUTHWESTERN PART OF THE GAMBO MAP AREA (NTS 2D/16)

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ABSTRACT

In the study area, the two principal geological divisions are the Gander Group and the Gander Lake Granite. The Gander Group consists of interbedded psammite, semipelite and pelite metamorphosed to greenschist or amphibolite facies. Approximately 60 percent of the map area is underlain by the Siluro-Devonian Gander Lake Granite, a predominantly massive, K-feldspar megacrystic and biotite-rich granite, which posttectonically intrudes the Gander Group. A static thermal aureole characterized by cordierite and andalusite hornfels occurs peripheral to the granite. This hornfels contrasts texturally with andalusite- and fibrolite-bearing schistose rocks associated with a syn- to late tectonic leucocratic granite west of Rodney Pond. Phyllonites near Square Pond contain kyanite, andalusite and sillimanite and are correlated with similar rocks to the north, near Gull Pond. The phyllonites define a regionally developed, high-strain zone termed the Wing Pond Shear Zone. Two small bodies of ultramafic rock occur in the Gander Group near Square Pond and Butts Pond.

INTRODUCTION

During the 1990 field season, the southeast corner of NTS map area 2D/15 (Gander Lake) and the southwest corner of NTS map area 2D/16 (Gambo) were mapped at 1:50,000 scale (Figures 1 and 2). This work represents a continuation of the mapping of the Gander Zone, initiated in 1986 in the Weir's Pond area (O'Neill, 1987).

The northern and eastern parts of the area are accessible from the Trans-Canada Highway and by boat from Gander Lake and Square Pond. The central and southern parts of the area can be accessed by four-wheel-drive and all-terrain vehicles from a system of logging roads, and by boat from Rodney Pond.

The topography of much of the area south of Gander Lake is gently undulating having local elevations rising to between 200 and 250 m. The land bordering Gander Lake, as far east as Joe's Brook on the southern shore and Soulis Brook on the northern shore, is steeply sloping and heavily wooded. Farther east on both sides, the land slopes gently toward the lake; a northeast-trending escarpment immediately west of Benton is responsible for this change in topography. The lineament so defined, controls the direction of flow of Soulis Brook. A major bend also occurs in Gander Lake where the lineament crosses the lake. Although the lineament is quite marked north of Gander Lake, there is no physiographic expression of it south of the lake. The most rugged topography occurs on the east side of Square Pond, where the land rises steeply to approximately 200 m and falls off steeply to Gambo Brook and Freshwater Bay. Peat bogs are extensive, particularly near Rodney Pond and Second Burnt Pond. In areas underlain by the Gander Lake Granite, boulder fields cover broad areas and the boulder type is predominantly megacrystic granite. In the wooded areas, spruce is the dominant tree type along with minor birch, fir and scattered pine.

South of Gander Lake, topographic lineaments are absent. The area is dissected by several small- to medium-sized ponds, the largest being Rodney Pond, by Joe's Brook, which flows to the northwest, and by an unnamed system of brooks that drain eastward from Rodney Pond through Second Burnt, First Burnt and Square ponds. The latter drains northeastward to Butts Pond, which drains into Freshwater Bay through Middle Brook. The gentle undulating topography that characterizes the area reflects the absence of a strong structural grain in the underlying bedrock and the presence of a boulder-rich till.

Although bedrock exposure is generally less than 1 percent throughout the area, the Gander Lake Granite is well exposed on the south shore of Gander Lake and there is also good exposure of the Gander Group on the northeast side of Square Pond.

PREVIOUS WORK

A detailed account of previous geological work in the area has been given in O'Neill (1990). Noranda Exploration Company Limited has carried out work in NTS map area 2D/16 near the Trans-Canada Highway, in metasedimentary rocks of the Gander Group; the report on Noranda's work is proprietary.

REGIONAL RELATIONSHIPS

The study area lies within the Gander Lake Subzone of the Gander Zone (Williams *et al.*, 1988). The Early

Ordovician and/or older Gander Group (Kennedy and McGonigal, 1972) underlies the eastern and western parts of the area, and has also been mapped northeastward to Carmanville (NTS 2E/8) (Currie and Pajari, 1977) and southwestward for approximately 100 km, to the Bay d'Espoir area (Dickson, 1987). Farther north, the Gander Group is interpreted to pass gradationally eastward into amphibolite-facies rocks of the Square Pond and Hare Bay gneisses (Blackwood, 1978). In the study area, the Gander Group is intruded by the megacrystic Gander Lake Granite, which underlies much of the area. Small bodies of a garnetiferous, muscovite granite, which occur in the western part of the map area, may be correlative with the Middle Ridge Granite to the southwest.

GENERAL GEOLOGY

GANDER GROUP–UNITS 1 AND 2

Approximately 40 percent of the map area is underlain by interbedded psammite, semipelite and pelite of the Jonathans Pond Formation (O'Neill and Knight, 1988) (Unit 1) of the Gander Group. The psammite is grey-weathered, thin- to medium-bedded and is generally in sharp contact with more pelitic layers. Quartzitic beds and concordant mafic bodies form a minor component of the formation. Four kilometres southwest of Rodney Pond, pink layers up to 2 cm thick occur in one exposure and appear to be coticules, a garnet- and quartz-bearing rock. A pervasive tectonic foliation and extensive metamorphic recrystallization have destroyed most of the sedimentary structures in the rocks. In the aureole of the Gander Lake Granite, weathered surfaces commonly have a pitted appearance and are typically bleached to a greyish-white, whereas fresh surfaces are dark blue to black and have a purple hue, where cordierite is present.

Several small exposures of dark grey to black pelite interbedded with psammite (Unit 2), occur northeast of the east end of Gander Lake. These rocks are along strike with the Indian Bay Big Pond Formation (see O'Neill, 1990), which includes black pelite, and are therefore, included with them. The contact between the formations was not observed.

ULTRAMAFIC ROCK AND DIABASE–UNIT 3

Two exposures of altered ultramafic rock were identified during mapping. One outcrop (subunit 3a) adjacent to the old railway line, 1 km west of Butts Pond (Figure 2), is weathered to a mottled to streaky, blueish grey and orange. The rock is completely altered to an assemblage of serpentine, talc and minor carbonate. A penetrative foliation developed in the rock is parallel to the regional foliation in the Gander Group. Immediately east of the ultramafic body, interbedded psammite, semipelite and pelite are exposed. However, there is an exposure gap between the metasedimentary and ultramafic rocks and therefore, the nature of the relationship between them is unknown. Distinctive micaceous green layers, several centimetres thick, form a minor component of the metasedimentary rocks. The micaceous rocks consist of alternating chlorite-rich and green hornblende-rich layers.

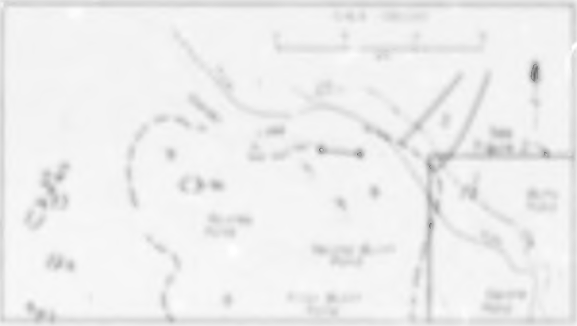

Figure 1. *Geology of the study area. The inset block in the southeast corner is shown in detail in Figure 2.*

LEGEND for Figures 1 and 2

SILURO-DEVONIAN OR OLDER

9 Gander Lake Granite: *Massive, K-feldspar megacrystic biotite granite;* **9a,** *equigranular phase having scattered megacrysts*

8 *Equigranular, leucocratic, garnetiferous muscovite-rich granite*

7 **7a,** *muscovite–biotite granite;* **7b,** *highly strained muscovite granite*

6 *Biotite granite*

5 *Hornblende granite*

4 *Hornblende gabbro*

3 *Ultramafic rock and diabase:* **3a,** *serpentine talc rock;* **3b,** *pyroxenite having minor colourless amphibole (and possible olivine), partly altered to serpentine and carbonate, in tectonic contact with* **3c,** *a fine-grained, banded diabase*

ORDOVICIAN OR OLDER
GANDER GROUP

2 Indian Bay Big Pond Formation: *interbedded, laminated black and greyish-green pelite and dark grey to grey sandstone*

1 Jonathans Pond Formation: *interbedded psammite, semipelite and greyish-green pelite predominantly metamorphosed to greenschist or amphibolite facies*

SYMBOLS

Geological contact, approximate

High-strain foliation

Primary flow foliation in granite

Bedrock exposure

Lineament, inferred from airphoto

Metamorphic minerals in high-strain zone are Sill = Sillimanite, Ky = Kyanite, And = Andalusite

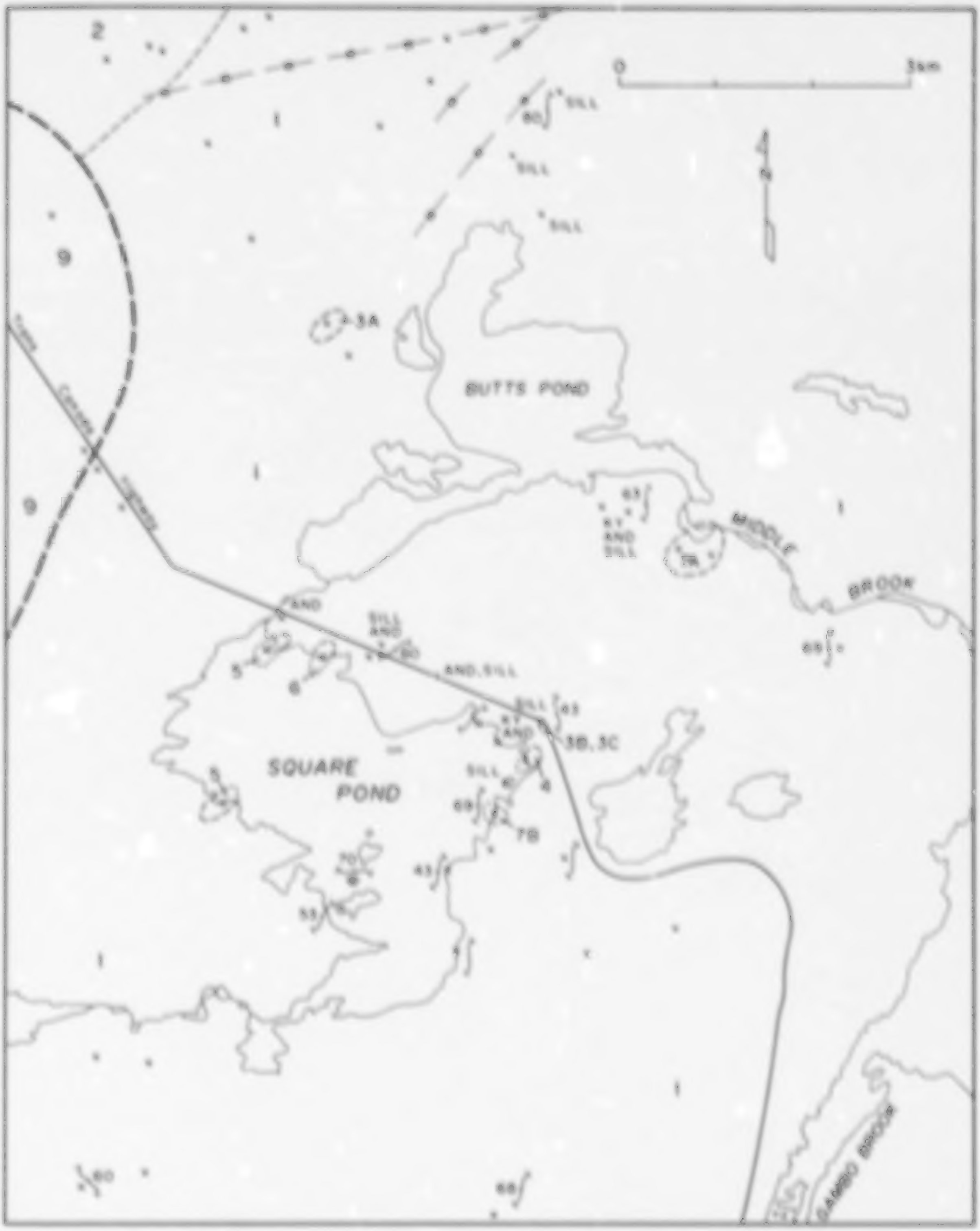
2
1
9
SILL
60
3A
BUTTS POND
KT AND SILL
MIDDLE BROOK
AND
SILL AND
AND, SILL
SQUARE POND
3B, 3C
7B
5
6
63
65
55
GAMBO BROOK
3 km

Figure 2. *Geology of the Square Pond and Butts Pond area, showing the location of the felsic, mafic and ultramafic bodies associated with the Wing Pond Shear Zone.*

A concordant biotite granite vein, less than a metre thick and containing disseminated pyrite, is interlayered with the metasedimentary rocks.

A body of ultramafic and mafic rock (subunits 3b and 3c) in tectonic contact with the psammite and semipelite of the Jonathans Pond Formation, is exposed in a roadcut on the Trans-Canada Highway, immediately north of the east side of Square Pond (Figure 2). The contact between the igneous and metasedimentary rocks is a shallowly dipping in the middle of the exposure, but dips steeply on the sides. The ultramafic rock is partly altered to serpentine and carbonate and is talcose in the foliated margins. Locally, fibrous serpentine occurs in the talc-rich zones. Clinopyroxene is locally preserved. Strongly foliated zones (possibly shear zones), also occur within the ultramafic body. On the top side of the exposure, the rock consists of a light-green weathering, fine-grained diabase (subunit 3c), which is cut by a network of quartz, calcite and epidote veins. The diabase has been recrystallized to green and blueish-green hornblende and minor quartz.

INTRUSIVE ROCKS–UNITS 4 TO 9

Several exposures of hornblende gabbro (Unit 4) occur at the north end of Square Pond. Boulders of gabbro are common on the southwest shore of Square Pond and in one locality south of the pond. The gabbro consists of coarse-grained green hornblende, plagioclase and minor opaque material and biotite and contains a heterogeneously developed high-strain foliation.

Two exposures of hornblende granite (Unit 5) occur on the north and southwest shores of Square Pond. In the southern locality, the granite is moderately foliated and consists of sericitized feldspar, quartz, green hornblende, chlorite, epidote and sphene. At the second locality, the granite is coarser grained, more weakly foliated and mineralogically similar to the first, although containing a greater proportion of hornblende.

One exposure of biotite granite (Unit 6) occurs on the north shore of Square Pond. The rock is foliated, medium grained and consists of quartz, plagioclase, microcline and biotite and minor epidote and sphene. The feldspars are moderately sericitized. The rock has been cataclastically deformed as some feldspars are cracked or broken.

Two exposures of muscovite- and biotite-bearing granite (subunit 7a) occur near the southeast corner of Butts Pond. The granite is white weathered, fine to medium grained, equigranular and massive.

Several small exposures of a leucocratic, muscovite-rich granite (subunit 7b) occur on the east shore of Square Pond. The granite locally contains a high-strain foliation and is spatially associated with gabbro (Unit 4).

Small bodies or sheets of a leucocratic, muscovite-rich granite (Unit 8) are exposed west of Rodney Pond (Figure 1). Many other exposures in the area, which contain predominantly metasedimentary rocks, also contain sheets of similar granite and pegmatite. The granite is white weathered, typically fine to medium grained, equigranular (grains range from 3 to 6 mm across) and consists of quartz, feldspar and muscovite and accessory garnet, biotite and pyrite. Quartz and feldspar occur in approximately equal amounts and muscovite forms approximately 20 percent of the rock; associated pegmatites are mineralogically similar. Although the granite is mostly massive, it is locally banded on a centimetre scale; individual bands are defined by alternating quartz- and feldspar-rich layers and micaceous layers; garnet is abundant in some bands and may form as much as 5 percent of the rock.

The granite is similar to that mapped farther north near Gillinghams Pond (O'Neill, 1990) and is mineralogically similar to the Middle Ridge Granite, as described by Blackwood (1981).

The Gander Lake Granite is characterized by abundant K-feldspar megacrysts that range up to 6 cm in length in a biotite, quartz and feldspar matrix, in which the crystals are up to 1 cm across. Feldspars are typically white weathered and form 60 to 70 percent of the rock; some are compositionally zoned. Quartz is greyish blue and averages approximately 20 percent of the matrix; biotite forms approximately 10 to 15 percent of the matrix. The feldspar megacrysts commonly contain small inclusions of biotite. Tourmaline is an accessory mineral but, in places, is concentrated in patches (which are 5 to 10 cm across).

The granite is massive in most exposures and boulders, however, a primary flow foliation is present in the northeastern part of the granite, close to its contact with metasedimentary rocks of the Gander Group (Plate 1). In many of the granite exposures on the shore of Gander Lake, the foliation is defined by feldspars and by elongate metasedimentary xenoliths, most likely derived from the Gander Group. The flow foliation trends approximately eastward and in one locality it is steeply dipping.

The proportion of xenoliths within the granite varies from less than 10 percent to approximately 70 percent. In some outcrops, the metasedimentary xenoliths stand out in positive relief.

The contact between granite and metasedimentary rocks is marked by a zone of sheeting, a metre or less across, in which granitic veins intrude along the tectonic foliation and/or bedding planes in the metasedimentary rocks (Plate 2). On a larger scale, e.g., along the shore of Gander Lake, granite exposures are tens of metres thick, and alternate with metasedimentary rocks; the latter are hornfelses, very hard and locally well-jointed. The granite adjacent to the contact, on the Trans-Canada Highway, is extensively shattered. Thin tourmaline-bearing, pegmatitic dykes commonly cut the metasedimentary rocks close to the contact. There is a noticeable lack of xenoliths in the granite close to the contact. This, along with the observation that the boundary between

Plate 1. *Elongate metasedimentary xenolith in the Gander Lake Granite, aligned parallel to the magmatic foliation defined by feldspars. Note compass for scale, near bottm left corner.*

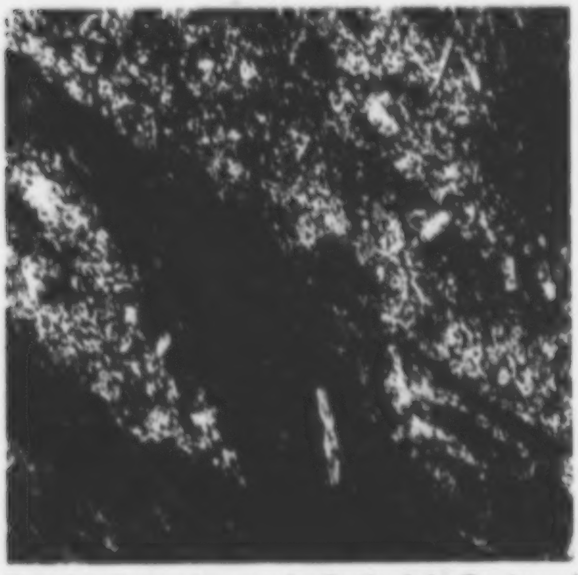

Plate 2. *Contact between the Gander Lake Granite and metasedimentary rocks of the Gander Group. Note the pick for scale at bottom of plate.*

xenolith and granite is typically very sharp (Plate 3), i.e., no assimilation of metasedimentary material, implies that the granite intruded relatively cool rocks.

Locally, the granite is cut by numerous, thin, quartz- and epidote-rich veins. Pegmatitic veins, which are generally tourmaline-bearing rarely occur and are less than 2 m thick. In one outcrop, the megacrystic granite is intruded by a leucocratic, equigranular, quartz–feldspar granite in which grain size ranges up to 3 mm. The contact is irregular and there is no obvious chilled margin. Elsewhere, a 10-cm-thick, fine-grained leucocratic granite dyke cuts the Gander Lake Granite and the margins of this dyke are overgrown by small megacrysts. In the boulder fields south of Second Burnt Pond, some megacrystic granite boulders contain fine-grained granite inclusions. The inclusions show rounded margins and contain some megacrysts.

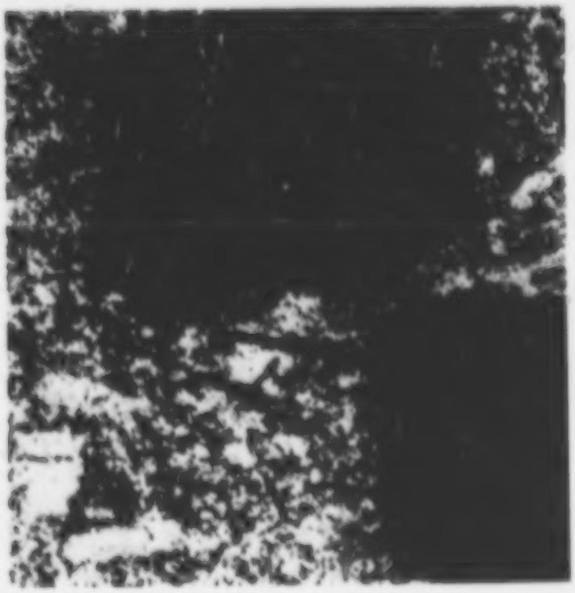

Plate 3. *Angular xenolith in the Gander Lake Granite. Note the sharp contact.*

Approximately 2 km north of the eastern end of Rodney Pond, an exposure of a finer grained variety of the Gander Lake Granite (subunit 9a) occurs (Figure 1). The granite contains quartz, feldspar and biotite and the average grain size is 3 mm. Disseminated megacrysts are up to 3 cm long and form less than 10 percent of the rock. Although the exposure is small, approximately 10 m across, this equigranular granite is the predominant rock type in boulders found in the immediate area, and this suggests that subunit 9a underlies a much more extensive area than that implied by the exposure.

METAMORPHISM

All of the sedimentary rocks mapped in the area have been metamorphosed to either greenschist or amphibolite facies and most of this metamorphism is attributable to nearby granitic intrusions. Kyanite schists, which occur near Square Pond, are not directly related to any granitic body and are discussed separately below.

Peripheral to the Gander Lake Granite, rocks of the Gander Group are thermally metamorphosed to hornfelses. Biotite, garnet, andalusite and cordierite are the principal index minerals in the aureole. In the northwest (near the mouth of Fifteen Mile Brook), there may be some overlap between metamorphic effects of the Gander Lake Granite and the leucocratic granite believed to be nearby (O'Neill, 1990).

Schistose rocks west of Rodney Pond contrast texturally with rocks in the aureole of the Gander Lake Granite. The pelitic and semipelitic rocks near the garnetiferous, leucocratic granite that outcrops west of Rodney Pond are typically medium- to coarse-grained schists. Biotite and garnet are developed near Rodney Pond as is andalusite and, locally, fibrolite. Sillimanite schist occurs farther west in the vicinity of the larger body of granite near Gillinghams Pond (O'Neill, 1990).

DEFORMATION

One principal tectonic foliation is defined throughout much of the Gander Group. This fabric is designated S_2 (so as to conform with fabric description established in the Weir's Pond area (O'Neill and Knight, 1988) and immediately north of the present map area; O'Neill, 1990). West of the Gander Lake Granite, S_2 has a shallow to moderate dip to the west and northwest. Locally, the foliation strikes north-northwest and has a shallow dip. The foliation is subhorizontal in places. On the southern shore of Gander Lake, where a small area of the Gander Group is partially enclosed by the Gander Lake Granite, S_2 strikes northeast and dips steeply northwest. This strike contrasts with the general trend of S_2 north of the lake but is parallel to a major lineament, which apparently controls the topography at the south end of Soulis Pond. The strike of S_2 also appears to bend and becomes sub-parallel to this lineament, north of the lake near Soulis Brook.

Several exposures of the Gander Group on the south side of the lake (south of Soulis Brook) are characterized by brecciation (Plate 4). The fragments within the breccia range up to approximately 5 cm across and are generally rounded to subrounded. The breccia has a quartz-rich matrix and occurs in zones approximately parallel to the foliation/bedding. The remainder of the exposure is dominated by psammite, which has a well-developed pressure solution cleavage. A similar breccia has been mapped on the north side of Home Pond. The brecciation is pre- or syn-metamorphism and may be the result of faulting.

East of Gander Lake, the S_2 foliation strikes north-northeast and dips moderately to steeply west-northwest. Locally, the main foliation is folded by mesoscopic scale, open to tight F_3 folds and by a crenulation lineation.

THE WING POND SHEAR ZONE

Schists, which exhibit a high-strain foliation and contain kyanite, sillimanite and andalusite, occur in several exposures northeast of Square Pond. Biotite-, muscovite- and hornblende-bearing granites and gabbro, outcrop as small bodies within or adjacent to the phyllonites and contain a weak to high-strain foliation. Phyllonites also occur south of Square Pond. The metamorphic assemblages, the high-strain foliation and the particular association of rock types, allows a correlation to be made with rocks exhibiting similar features along strike in the Wing Pond and Gull Pond areas (O'Neill and Knight, 1988; O'Neill, 1990). The correlation is further strengthened by a regional, positive aeromagnetic anomaly, which is coincident with the shear zone throughout its strike length. Exposures of gabbro and biotite or hornblende granite in the Wing Pond, Gull Pond and Square Pond areas and of ultramafic rock near Square Pond and Butts Pond are spatially associated with the shear zone, which suggest that the aeromagnetic anomaly is due to a large mafic-ultramafic body, occurring at depth. This zone of rocks exhibiting a high-strain foliation is termed the Wing Pond Shear Zone, after the area where the most extensive exposures of phyllonites is found. The shear zone is considered to be a regional feature, at least 40 km long and up to 3 km wide, locally. If the interpreted correlation with the aeromagnetic anomaly is correct, then the shear zone continues southward along strike because the anomaly continues at least as far south as the Maccles Lake Granite.

Plate 4. *Subrounded fragments in breccia zone in metasedimentary rocks of the Gander Group, southern shore of Gander Lake.*

In the vicinity of Square Pond, the high-strain foliation strikes north to north-northeast and predominantly dips steeply northwest. Concordant, pretectonic granitic and gabbroic bodies also locally contain the high-strain foliation. A preliminary examination of the asymmetry of the foliation and syntectonic folds in the area suggest a dextral sense of shear. Near Square Pond, tight, upright folds are developed in psammite and semipelite and their axial planes are sub-parallel to the high-strain foliation of the Wing Pond Shear Zone. These folds fold the regionally developed solution seam or pin-stripe banding (S_2) in the Gander Group and are therefore termed F_3. The sub-parallel nature of the S_3 and high-strain foliations suggests that their development may be related.

The juxtaposition of low- to medium-pressure rocks with metasedimentary rocks at chlorite grade, which is apparently characteristic of the Wing Pond Shear Zone, suggests a significant dip-slip component of motion, in addition to the strike-slip component. The relative timing of the dip-slip and strike-slip components is unknown. At least locally, the high-strain zone coincides with the southeastern margin of the Indian Bay Big Pond Formation. Because of the significant dip-slip component of motion in the zone, the kyanite-, andalusite- and sillimanite-bearing phyllonite may not necessarily represent part of the Gander Group. If the phyllonite is part of the group, it is not clear which of the Jonathan's Pond or Indian Bay Big Pond formations it represents. The presence of the shear zone also implies that the Gander Group is not a continuous sequence.

Farther east toward Gambo, and away from the high-strain zone, the grade of metamorphism decreases. This decrease was also observed east of Wing Pond.

Based on mapping in the eastern Gander Lake Subzone, Blackwood (1977, 1978) defined the Square Pond Gneiss as a paragneiss unit, which he interpreted as equivalent to the Gander Group but at a higher metamorphic grade. He concluded that the Square Pond Gneiss was separated from the Hare Bay Gneiss by a migmatite front. The Square Pond Gneiss encompasses greenschist- and amphibolite-grade rocks in the Ocean Pond, Wing Pond and Square Pond areas and farther south. However, recent mapping (O'Neill and Lux, 1989; O'Neill, 1990 and this paper) has shown that 1) although the protolith (the Gander Group) remains the same throughout, the type of metamorphism is variable in the Square Pond Gneiss, 2) the metasedimentary rocks do not represent part of a prograde (west to east) sequence, and 3) the metasedimentary rocks are not gneisses. In the Ocean Pond area, the regionally metamorphosed rocks define a low pressure—high temperature type of metamorphism associated with the foliated, garnetiferous, leucocratic Ocean Pond Granite (O'Neill and Lux, 1989). North of Four Mile Pond, the metamorphic rocks represent the thermal aureole to the posttectonic Deadmans Bay Granite. Metamorphic rocks in the Wing Pond area are distinct again and have been described in O'Neill and Lux (1989; see above, Wing Pond Shear Zone). Therefore, it is recommended that the term Square Pond Gneiss be dropped and the rocks included under this term revert to their former status as part of the Gander Group.

It is important to emphasize that east of the Wing Pond Shear Zone in the Wing Pond area and near Gambo, the metamorphic grade actually decreases. Thus, metamorphic rocks in the Gander Lake Subzone do not represent the effects of one progressive regional (west to east) metamorphic event. Hence, the Hare Bay Gneiss does not represent a culmination of any such regional metamorphic process, but represents a more localized metamorphism spatially associated with the eastern boundary of the Gander Zone. The timing of the various metamorphic and structural events is uncertain.

ECONOMIC GEOLOGY

Quartz veins are profusely developed in many exposures of the Gander Group, however, no obvious mineralization was noted. A gossan, 1 to 2 m thick, occurs within the eastern part of the ultramafic body (subunit 3b) exposed in a roadcut on the Trans-Canada Highway; much of the gossan is a brown mud.

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REFERENCES

Blackwood, R.F.
1977: Geology of the Hare Bay area, northwestern Bonavista Bay. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-1, pages 7-14.

1978: Northeastern Gander Zone. *In* Report of Activities for 1977. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-1, pages 72-79.

1981: Geology of the west Gander Rivers area, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 81-1, pages 50-56.

Currie, K.L. and Pajari, G.E.
1977: Igneous and metamorphic rocks between Rocky Bay and Ragged Harbour, northeastern Newfoundland. *In* Report of Activities, Part A. Geological Survey of Canada, Paper 77-1A, pages 341-346.

Dickson, W.L.
1987: Geology of the Mount Sylvester (2D/3) map area, central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 283-296.

Kennedy, M.J. and McGonigal, M.H.
1972: The Gander Lake and Davidsville Groups of northeastern Newfoundland: new data and geotectonic implications. Canadian Journal of Earth Sciences, Volume 9, pages 452-459.

O'Neill, P.P.
1987: Geology of the west half of the Weir's Pond (2E/1) map area. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 271-281.

1990: Geology of the northeast Gander Lake map area (NTS 2D/15) and the northwest Gambo map area (NTS 2D/16). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 317-326.

O'Neill, P. and Knight, I.
1988: Geology of the East half of the Weir's pond, 2E/1, map area and its regional significance. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 165-176.

O'Neill, P. and Lux, D.
1989: Tectonothermal history and ^{40}Ar/^{39}Ar geochronology of northeastern Gander Zone, Weir's Pond area (2E/1). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 131-139.

Williams, H., Colman-Sadd, S.P. and Swinden, H.S.
1988: Tectonic-stratigraphic subdivisions of central Newfoundland. *In* Current Research, Part B. Geological Survey of Canada, Paper 88-1B, pages 91-98.

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Geological Survey Branch, Report 91-1, pages 175-178

GRAPTOLITES FROM THE BAIE D'ESPOIR GROUP, SOUTH-CENTRAL NEWFOUNDLAND

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ABSTRACT

Graptolites are reported from four localities in the Baie d'Espoir Group. Both the assemblages and rock types suggest a correlation with the Middle–Upper Ordovician Lawrence Harbour Formation ('Caradoc black shale') and the overlying Point Leamington Formation of the Badger–Grand Falls–Notre Dame Bay region. The faunas described in this article double the number of known fossiliferous localities in the Baie d'Espoir Group; this suggests that many more remain to be discovered despite the intense tectonic deformation present throughout the area, and that these will prove invaluable in refining the stratigraphy of the region.

STRATIGRAPHY AND PREVIOUS FOSSIL RECORDS OF THE BAIE D'ESPOIR GROUP

The Baie d'Espoir 'Series' was first proposed by Jewell (1939); it was subsequently given group status by Anderson (1967), then redefined and subdivided into five formations by Colman-Sadd (1976, 1980, 1985), including the Salmon River Dam, St. Joseph's Cove, North Steady Pond, Riches Island and Isle Galet formations. The Isle Galet Formation is present only in the southern part of the region (Colman-Sadd, 1974, 1976; Dickson, 1987), but is considered to rest conformably on the Riches Island Formation; of the remaining units, the Salmon River Dam Formation is considered the oldest, followed by the St. Joseph's Cove and Riches Island formations, which appear to be lateral equivalents at least in part, whereas the North Steady Pond Formation is thought to gradationally overly the St. Joseph's Cove Formation (Colman-Sadd, 1980).

Despite the substantial geographical area covered by the Baie d'Espoir Group, paleontological data from the unit is sparse, presumably due mainly to the ubiquitous tectonic deformation. Middle Ordovician graptolites were reported by Baird *et al.* (1951) and Anderson and Williams (1970) from 'Grapto Lake' (Middle Ridge Pond) in the Great Gull Map area. They were identified by A.E. Wilson and L.M. Cunning (*in* Anderson and Williams, 1970) as '*Climacograptus bicornis*, *Climacograptus* sp. cf. *C. styloideus* and *Climacograptus* sp. cf. *C. scharenbergi*'. Dunlop (1954) reported a single, poorly preserved gastropod identified as ?*Eotomaria* sp. from near the mouth of Little River opposite the southern end of Riches Island, which was considered to indicate an Ordovician (probably Middle Ordovician) age. A fragment of a trilobite pygidium was also recorded from the Isle Galet Formation near Baraway de Cerf, which was tentatively dated as Late Cambrian to Early Ordovician. Anderson (1967) recorded *Streptelasma* and crinoidal debris from near St. Alban's, which probably originated from the St. Joseph's Cove Formation and indicated an Ordovician or younger age (Colman-Sadd, 1976). Brachiopods (identified as orthids, cf. *Orthambonites* and cf. *Productorthis* by R.B. Neuman *in* Colman-Sadd, 1976), bryozoans and pelmatozoans were subsequently discovered near the mouth of the Conne River by Colman-Sadd (1976) from the Riches Island Formation close to its contact with the St. Joseph's Cove Formation. An Ordovician age, somewhere between late Arenig and early Caradoc inclusive, was deduced. During exploration by Esso Minerals Canada (M. Lenters, written communication to S.P. Colman-Sadd, 1987), additional crinoidal material was recorded from metamorphosed calcarenite along the Southeast Pond logging road near the junction between Highway 360 and the Milltown–St. Alban's junction, which could possibly have originated from the same unit collected by Colman-Sadd (1976).

In conclusion, it may be stated that the only reliable age recorded previously was provided by the Middle Ordovician graptolite fauna at Middle Ridge Pond, indicating the *N. gracilis* or *D. multidens* zones of the standard British sequence. The remaining evidence appeared to suggest an Ordovician age, but even that was not certain in some cases.

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* Lithoprobe contribution #216

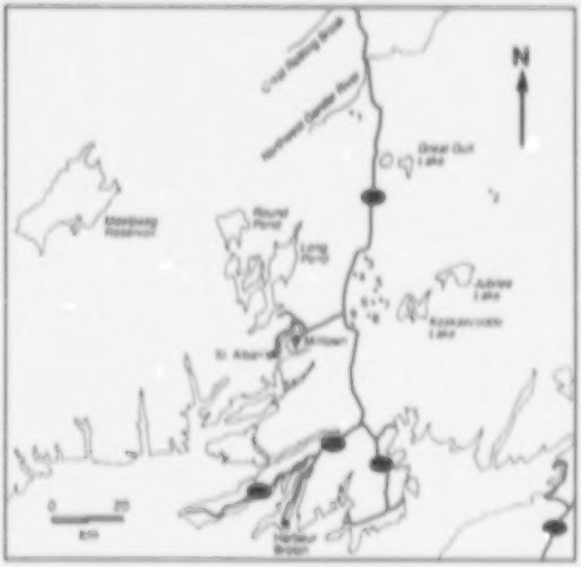

Figure 1. *Map of Baie d'Espoir region, showing position of localities discussed in text.*

DESCRIPTION OF NEW LOCALITIES AND FAUNAS

During the summers of 1989 and 1990, a number of localities were visited where black, graphitic phyllites or schists had been recorded by previous workers (Anderson and Williams, 1970; Colman-Sadd, 1976, 1980; T. Rivers, personal communication, 1989; M. Lenters, written communication to S.P. Colman-Sadd, 1987). Surprisingly, several of these yielded graptolites which, although mostly too poorly preserved to allow full taxonomic identification, were sufficient to permit an approximate age identification of the units.

NORTHWEST GANDER RIVER (Figure 1, Locality 1)

Location. Exposures in a 1 km length of logging road running 500 m south of the Northwest Gander River, 3 km southeast of the Little Gull River and accessible from the Baie d'Espoir highway (Geographic location 48°20'N 55°30'W).

Lithology. A transitional (but tectonically broken) section is present, from siliceous black shale to the west, through more fissile, silty black shale to alternating black and grey shale and fine grey sandstone to the east. The shales are deformed, but lack a penetrative cleavage.

Graptolites. A variety of forms seem to occur, but further collecting is required before distinct biostratigraphic intervals may be demonstrated. The most fossiliferous interval, about halfway along the outcrop, yielded distal dicranograptid fragments (*i.e.*, *Dicranograptus* or *Dicellograptus*), *Climacograptus* sp., *Orthograptus calcaratus* and *Corynoides* sp. cf. *C. calicularis*.

Age and Correlation. The assemblage indicates a Middle Ordovician age of *D. clingani Zone* or earlier. The succession of rock types along the section is identical to that found in the Lawrence Harbour Formation and in the transition to the overlying Point Leamington Formation (Williams, *in press*). No outcrop was present at this location when mapped by Colman-Sadd (1985); his inferred assignment of the area to Unit 8 of the Coy Pond Complex (brecciated and sheared serpentinite and magnesite-rich rock) is thus, clearly in need of revision, the shale probably belonging to the same unit seen at Middle Ridge Pond and elsewhere.

MIDDLE RIDGE POND (Figure 1, Locality 2)

Location. Small outcrops along lakeside at extreme southern end of Middle Ridge Pond (Geographic location 48°16'N 55°8'W).

Lithology. The graptolitic material is composed of heavily cleaved, fissile black shale, and is apparently in gradational contact with sandstone. Other outcrops ca. 100 m to the east include more siliceous black shales, which did not yield graptolites.

Graptolites. The deformation makes specific identification impossible. Forms present include *Dicellograptus* sp., *Climacograptus* sp. and *Orthograptus* sp. cf. *calcaratus*.

Age and Correlation. The fauna listed above indicates a middle or upper Ordovician age. If the assemblage recorded previously by Baird *et al.* (1951) and Anderson and Williams (1970) was identified correctly, it would give a more precise correlation with the Middle Ordovician *N. gracilis* or *D. multidens* zones. However, the different rock types present at the locality do suggest that more than one stratigraphic interval is exposed.

CONNE RIVER (Figure 1, Locality 3)

Location. Exposures on southwest river bank of Conne River 400 m southeast of Baie d'Espoir highway (Grid Ref. XD 120 329).

Lithology. Black fissile shale heavily cleaved at a high angle to bedding, with extensive secondary pyritization indicating thermal metamorphism. Some paler grey sandstone also present.

Graptolites. None recovered.

Age and Correlation. Although no graptolites were recovered, the lithology is similar to that present at localities 1 and 2. A tentative correlation with the upper part of the Lawrence Harbour Formation and its equivalents is therefore suggested on purely lithological grounds.

TWILLICK BROOK (Figure 1, Locality 4)

Location. Exposures along river 50 to 100 m east of the Baie d'Espoir highway (Geographic location 48°4'N 55°34'W).

Lithology. Siliceous and fissile black shale exposed for over 150 m oblique to strike, with slightly developed cleavage apparently parallel to bedding and structural slices of paler grey, coarse sandstone in the southern part of the outcrop.

Graptolites. None recovered.

Age and Correlation. The reason for the absence of graptolites is unclear, as both rock types and lack of intense structural deformation would seem ideal for their preservation, although it is possible that thermal metamorphism was responsible for their destruction. The black shale lithology is identical to the lower part of the Lawrence Harbour Formation, and occurs adjacent to the (underlying?) felsic pyroclastic rocks of the Twillick Brook Member of the St. Joseph's Cove Formation (Colman-Sadd, 1980).

NO NAME HILLOCK (Figure 1, Locality 5)

Location. Small hill 2 km north of Little River Lake (Grid Ref. XD 118 198).

Lithology. Highly deformed, dark grey 'pencil slate' having crenulation cleavage.

Graptolites. Surprisingly, poorly preserved graptolites are discernable on some surfaces; however, identification is impossible.

Age and Correlation. Little can be deduced from the graptolites, but the unit is lithologically similar to that seen at the other localities.

LITTLE RIVER LAKE (Figure 1, Locality 6)

Location. Southern tip of small peninsula along northwest shore of lake (Grid Ref. XD 118 174).

Lithology. Highly deformed slate associated with crenulation cleavage.

Graptolites. None recovered.

Age and Correlation. Lithologically identical to unit seen at locality 5.

LITTLE RIVER LAKE (Figure 1, Locality 7)

Location. Southern tip of elongate island at northeast end of lake (Grid Ref. XD 122 168).

Lithology. Mostly grey sandstone and sheared conglomerate associated with minor heavily cleaved grey shale.

Graptolites. None recovered.

Age and Correlation. Unknown, although the rocks look very similar to the sandstones and conglomerates of the Point Leamington Formation (Williams, *in press*).

POWERLINE NEAR LITTLE RIVER (Figure 1, Locality 8)

Locality. Under power line 1.5 km southwest of Little River Lake (Grid Ref. XD 092 108).

Lithology. Black and grey phyllites associated with crenulation cleavage.

Graptolites. None recovered.

Age and Correlation. Unknown, but exposure is along strike from localities 5 and 6.

SOUTHEAST POND ROAD (Figure 1, Locality 9)

Location. Two outcrops on the northwest side of Southeast Pond Road, 1.5 km north-northeast from its junction with the Baie d'Espoir highway, 2 km south of junction with highway 361 (Geographic location 47°37.15'N 55°36.30'W).

Lithology. Grey, heavily cleaved, fissile shale, crenulation cleavage locally present.

Graptolites. Despite intense deformation, graptolites are clearly visible including dicranograptid fragments (i.e., *Dicranograptus* or *Dicellograptus*) and large diplograptids reminiscent of *Climacograptus tubuliferus*.

Age and Correlation. The unit is Middle or Late Ordovician in age, and once again is probably a correlative of the Lawrence Harbour Formation. The shales are adjacent to metamorphosed limestones containing crinoid ossicles; these possibly belong to the same unit from which Colman-Sadd (1976) recovered articulate brachiopods.

CONCLUSIONS

All the fossiliferous localities described here are of middle Ordovician age, with similar graptolite zonal range to those present in the Lawrence Harbour Formation of the Badger–Grand Falls and Notre Dame Bay regions (Williams, 1988, *in press*). With the exception of that near the Northwest Gander River, all localities fall within areas previously mapped as St. Joseph's Cove and Riche Island formations; they probably represent a single lithostratigraphic unit, which is almost certainly a lateral equivalent of the Lawrence Harbour Formation, and should probably be given distinct formational status within the Baie d'Espoir Group. All outcrops are apparently structurally isolated from adjacent rock units, except for that near the Northwest Gander River, which exhibits a gradational change from black siliceous shale, through black silty shale, to alternating black shale and fine, grey sandstone; this is identical to the transition from Lawrence Harbour Formation to Point Leamington Formation as described and redefined by Williams (*in press*). Therefore, it is suggested that the outcrops discussed here demonstrate that black shale deposition of the Lawrence Harbour Formation was even more extensive than previously recognized, occurring throughout the entire Exploits Subzone of the Dunnage Zone. Furthermore, the frequent structural repetition seen in the Baie d'Espoir Group is very similar to that suggested by Williams (1989) for the Grand Falls–Badger–Red Indian Lake region to the northeast and confirmed in part by Evans *et al.* (1990).

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REFERENCES

Anderson, F.D.
1967: Structural studies in the Baie d'Espoir Group, Newfoundland. *In* Collected Papers on Geology of the Atlantic Region–Hugh Lilly Memorial Volume. *Edited by* E.R.W. Neale and H. Williams. Geological Association of Canada, Special Paper 4, pages 193-200.

Anderson, F.D. and Williams, H.
1970: Gander Lake (west half), Newfoundland. Geological Survey of Canada, Map 1195A.

Baird, D.M., Scott, H.S., Moore, J.C.B. and Walker, W.
1951: Reconnaissance geology of east-central Newfoundland between Sir Charles Hamilton Sound and Baie d'Espoir. Photographic Survey Corporation Limited, Unpublished report, 155 pages.

Colman-Sadd, S.P.
1974: The geologic development of the Bay d'Espoir area, southeastern Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, 271 pages.

1976: Geology of the St. Alban's map area, Newfoundland (1M/13). Newfoundland Department of Mines and Energy, Mineral Development Division, Report 76-4, 19 pages.

1980: Geology of the Twillick Brook map area, Newfoundland (2D/4). Newfoundland Department of Mines and Energy, Mineral Development Division, Report 79-3, 23 pages.

1985: Geology of the Burnt Hill map area (2D/5) Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-3, 94 pages.

Dickson, W.L.
1987: Hungry Grove Pond (Provisional Map). Newfoundland Department of Mines and Energy, Mineral Development Division, Map 87-56.

Dunlop, W.B.
1954: Exploration of the Bay d'Espoir area. Newfoundland and Labrador Corporation, Unpublished company report. Newfoundland Department of Mines and Energy, Geological Survey Branch.

Evans, D.T.W., Kean, B.F. and Dunning, G.R.
1990: Geological studies, Victoria Lake Group, central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 131-144.

Jewell, W.B.
1939: Geology and mineral deposits of the Baie d'Espoir area. Newfoundland Geological Survey, Bulletin 17, 29 pages.

Williams, S.H.
1988: Middle Ordovician graptolites from central Newfoundland. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 183-188.

1989: Age and provenance of Ordovician rocks along Lithoprobe East Vibroseis Transect: determination based on graptolite studies. *In* Lithoprobe East, report of transect meeting October 19-20, 1989, St. John's, Newfoundland. *Edited by* G.M. Quinlan. Memorial University of Newfoundland, St. John's, pages 84-89.

In press: Stratigraphy and graptolites of the Upper Ordovician Point Leamington Formation, central Newfoundland. Canadian Journal of Earth Sciences, Volume 29.

Current Research (1990) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 90-1, pages 179-183

THE PETROGENESIS AND EMPLACEMENT OF PROTEROZOIC DYKE SWARMS, PART 2: GEOCHEMICAL PROCESSES AND PALEOSTRESS ANALYSIS

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ABSTRACT

The Early Proterozoic Kikkertavak dyke swarm of the Hopedale Block, Labrador, exhibits features that reflect the large-scale crust–mantle processes of magma genesis and emplacement common to many Proterozoic dyke swarms; this invites comparison both with other Proterozoic swarms and their smaller scale Phanerozoic equivalents. Good exposure of the Kikkertavak dyke swarm also allows the study of local magmatic and tectonic factors.

INTRODUCTION

Proterozoic dyke swarms, which have intruded into previously permobile Archean terranes, are found on every continent. Two such swarms are well preserved and exposed in the Hopedale Block of Labrador, allowing the study and comparison of primary petrological and structural aspects, both on a regional and on a local basis. The Kikkertavak dyke swarm, dated at 2200 Ma (Rb–Sr whole-rock date, B.J. Fryer, in Grant *et al.*, 1983), was chosen for an intensive and integrative study of existing geochemical, magmatic flow and swarm emplacement models. The younger Harp dyke swarm, dated at 1200 Ma (Rb–Sr whole-rock date, F.R. Voner, *in* Ermanovics *et al.*, 1982; Grant *et al.*, 1983), was also studied and sampled, although less intensively, for comparison purposes with the Kikkertavak swarm. The initial research results are presented in this paper.

PREVIOUS WORK

Little detailed research has been done on the Hopedale Block. The present evolutionary history of the area is based on regional 1:100,000-scale mapping by the Geological Survey of Canada (GSC) (Ermanovics, 1979, 1980, 1981a,b, 1984; Ermanovics and Raudsepp, 1979; Ermanovics and Korstgaard, 1981; Ermanovics *et al.*, 1982). The GSC focus has been to establish the petrological, geochronological and structural aspects of the Archean gneisses (e.g., Korstgaard and Ermanovics, 1984). Earlier work in the area has also concentrated on structural and metamorphic histories (e.g., Taylor, 1971) and correlation with similar terrains in West Greenland (e.g., Sutton *et al.*, 1972).

Apart from brief descriptions in the GSC reports, very little data are available on the Kikkertavak dykes. The Harp dykes, a series of younger intrusions within and adjacent to the Harp Lake anorthosite–gabbro plutonic complex situated approximately 100 km west of the present study area, have been investigated by Meyers and Emslie (1977).

Previous work as part of this project (1989) concentrated on intensive geochemical sampling of both swarms, in a limited area, in the centre of the Hopedale Block, and on the study of dyke–host-rock relationships and modes of dyke emplacement and dilation.

GEOLOGICAL SETTING OF THE DYKE SWARMS

The Hopedale Block lies in the southern part of the Nain Province, adjacent to the Churchill Province in the west and the Makkovik Province in the southeast (Figure 1). It consists of polydeformed, mainly granodioritic to tonalitic gneisses having a predominantly northeast–southwest (Fiordian)

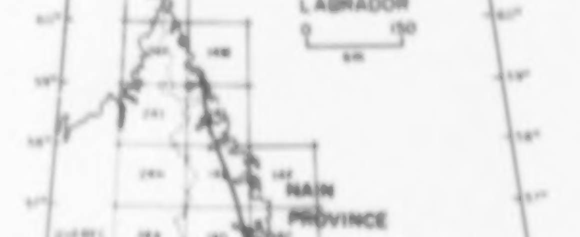

Figure 1. *Location of the Hopedale Block, Labrador. Study area shown in black.*

trend. The Fiordian-trending fabrics are interpreted by Ermanovics *et al.* (1982) to be late Archean and postdate the predominantly pretectonic Kanairiktok Intrusive Suite at about 2830 Ma (U–Pb *zircon* concordia, Loveridge *et al.*, 1987). The Fiordian trend overprints an earlier northwest–southeast (Hopedalian) trend that is preserved around and to the northwest of the village of Hopedale (Figure 2, Plate 1) and which gives U–Pb *zircon* and Rb–Sr whole-rock dates in the range between 3250 and 3000 Ma (Grant *et al.*, 1983; Loveridge *et al.*, 1987). Within both the Fiordian and Hopedalian domains, subvertical planar and linear fabrics show strong parallelism, suggesting block-wide, shear-zone deformation in both cases. The Fiordian-trending gneisses, which dominate the study area, are deformed agmatitic gneisses containing some amphibolite bands. The gneisses are at amphibolite facies, possibly retrogressed from a granulite-facies assemblage. Any earlier structural and metamorphic histories were largely erased by the Hopedalian event (Ermanovics *et al.*, 1982).

The post-Fiord-trend dykes are conspicuous as rectiplanar and irregular intrusive masses throughout the Hopedale Block and are superbly exposed along the ice-scoured coastline of the mainland and island archipelago, north of Kanairiktok Bay (Figure 2). Consequently, this area was chosen for detailed investigation, and fieldwork was undertaken mainly by boat.

Fieldwork done in 1989 concentrated on further geochemical sampling and the study of dyke–fissure dilation as a means to understanding the stress systems that acted on the Hopedale Block. Samples for rock magnetism studies (paleomagnetism and magnetic anisotropy) and U–Pb zircon dating were collected from both swarms. The macroscopic textures present within the Kikkertavak dykes were also examined. Work in 1989 also concentrated on enlarging the geographical spread of data. However, as a consequence of logistics, the study was confined to coastal areas and covered only a fraction of the total area of the Hopedale Block.

GEOCHEMISTRY AND PETROLOGY OF THE KIKKERTAVAK DYKES

MINERALOGY AND PETROLOGY

Four hundred and forty samples for geochemical analysis were collected in the Hopedale Block concentrating on the older (2.2 Ga) Kikkertavak dyke swarm but with some limited sampling of the Harp dykes (1.2 Ga). The study of geochemical variation on a regional and local basis was attempted, utilizing a geographic spread of localities and along-length or across-width sampling of individual dykes.

In thin section, the Kikkertavak dykes display a primary mineralogy of augite, plagioclase, ilmenite, magnetite and apatite. Plagioclase is the dominant phenocryst phase and may form megacrysts 5 to 15 cm long. These occur in extremely phyric, margin-parallel, laterally persistent layers in otherwise aphyric diabase (Plates 2 and 3). The texture is unique to the Kikkertavak swarm but is not present in most dykes of the suite and does not occupy a specific geographic area. Smaller phenocrysts (1 to 5 cm in length) are more common in Kikkertavak diabases than the megacrysts, and are similarly layered. The segregations into phyric and aphyric layers are regarded as a flow differentiation or differential accretion structure (see below). Glomeroporphyries of the smaller phenocrysts are common within the phyric layers (Plate 4). Other Kikkertavak diabases are aphyric, or plagioclase phyric with no flow differentiated structure or megacrysts. Coarser grained gabbroic dykes contain singular megacrysts but the differentiated phyric–aphyric structure is rare except in their diabase margins.

Augite forms a minor phenocryst phase in Kikkertavak dykes but is never visible as such in hand specimen; it is often best preserved as microphenocrysts along with plagioclase in glassy chilled margins or in fine-grained diabases.

The groundmass in the Kikkertavak dykes consists of ophitic plagioclase and augite with ilmenite and magnetite. The latter occurs as rims around ilmenite cores and as separate crystals, which may nucleate on pyroxene phenocrysts; apatite is a rare accessory phase. In contrast, the Harp dykes are rarely porphyritic and never megaphyric. In thin section, they show a simple mineralogy of olivine, augite, plagioclase and an opaque phase or phases.

ALTERATION

Locally, Kikkertavak dykes are altered to greenschist–lower-amphibolite-grade rocks in the mid-Proterozoic Kanairiktok shear zone (Ermanovics *et al.*, 1982), which forms the southern boundary of the Hopedale Block against the Makkovik Province (Figure 2). Within 5 km of the shear zone, augite develops actinolitic rims and plagioclase is heavily altered to sericite. Augite is unaltered at greater distances from the shear zone but variable sericitization of feldspar is seen throughout the area. Dyke margins are frequently sheared south of Kijuksuatalik Island (Figure 2). The low-grade metamorphism gives a characteristic greenish hue to many Kikkertavak dykes and distinguishes them from the non-metamorphosed Harp dyke swarm. Plagioclase in the Harp dykes shows only low degrees of seritization and augite is never severely altered. However, olivine is commonly partially or completely altered to serpentine even in dykes, where the remaining mineralogy shows little or no alteration.

MAJOR-ELEMENT GEOCHEMISTRY

Major-element plots of the Kikkertavak dykes are shown in Figures 3 to 5. Preliminary analysis of the geochemical trends indicates strong similarities to the trends of continental-flood basalt provinces, such as the Deccan Traps and Karoo lavas or the Tertiary Columbia River flood basalts. For example, the plot of calcium versus magnesium (Figure 3) shows two distinct geochemical groups; a large dataset of tholeiitic (low MgO) magmas with a positive correlation between calcium and magnesium and a small set of picritic

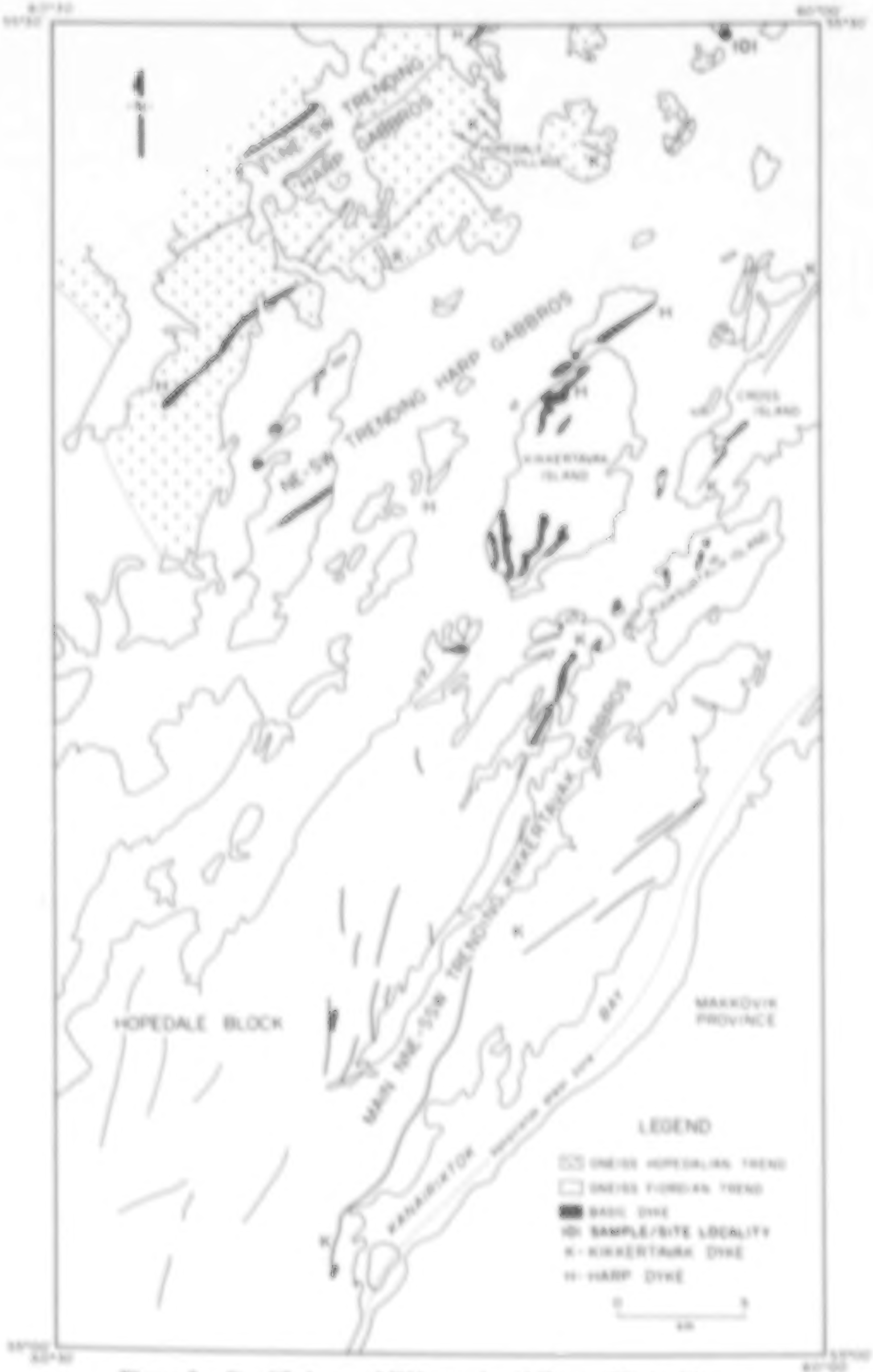
101
ENE-SW TRENDING HARP GABBROS
HOPEDALE VILLAGE
NE-SW TRENDING HARP GABBROS
KIKKERTAVAK ISLAND
CROSS ISLAND
MAIN NNE-SSW TRENDING KIKKERTAVAK GABBROS
HOPEDALE BLOCK
MAKKOVIK PROVINCE
KANAIRIKTOK BAY
H
K
LEGEND
GNEISS HOPEDALIAN TREND
GNEISS FIORDIAN TREND
BASIC DYKE
101 SAMPLE/SITE LOCALITY
K - KIKKERTAVAK DYKE
H - HARP DYKE
0
5
km

Figure 2. *Simplified map of Kikkertavak and Harp gabbroic dykes.*

Plate 1. *Aphyric Kikkertavak dyke intruding conformably into Hopedalian-trending gneiss. Note planar Hopedalian foliation.*

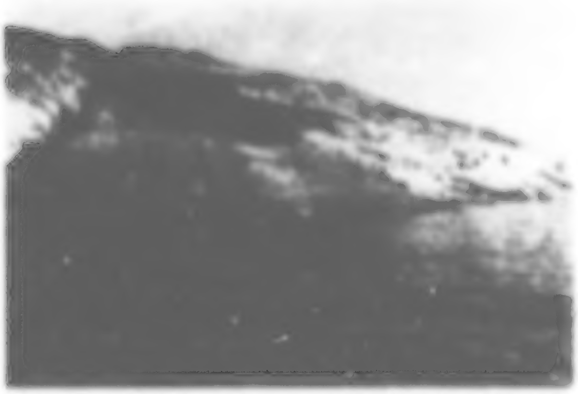

Plate 2. *Highly flow-differentiated Kikkertavak gabbro dyke. The central phyric band in the dyke contained plagioclase megacrysts up to 10 cm in length. Plagioclase phenocrysts made up to 80 percent of the rock in this 3-m-wide zone. The dyke is 23 m wide.*

Plate 3. *Thin, laterally persistent phyric–aphyric bands resulting from differential accretion of plagioclase phenocrysts at locality KII (Platten and Watterson, 1987).*

(high MgO) magmas. If the lower magnesian samples have evolved from the picrites, olivine is the most likely phase to have been fractionated. The lack of olivine, in thin sections of the Kikkertavak dykes and the large gap between the two datasets, suggests that this process was complete at the presently exposed crustal level, probably because dense picritic liquids would have difficulty travelling upward through the crust and would therefore remain pooled at the moho until fractionated (Huppert and Sparks, 1985). However, in many petrological suites, picrites and non-picrites are genetically unrelated (J. Tarney, personal communication, 1989). Hence, if indeed the tholeiites were derived from the picritic dykes, a Ca-rich phase such as plagioclase or pyroxene must have fractionated with olivine. Alternatively, the picrites could represent olivine-rich cumulates resulting from the fractionation of these phases.

The broad calcium–magnesium correlation of the dataset suggests that after the fractionation of olivine was completed, clinopyroxene, and possibly plagioclase, became fractionating phases. This in a low-pressure process (Cox, 1980) and therefore suggests an upper crustal setting for the Kikkertavak dyke swarm exposed today. Superimposed on the dataset for the Kikkertavak dykes, on Figure 3, is the proposed fractionation path combined, from data from the Karoo and Deccan flood basalt provinces and associated dykes (Cox,

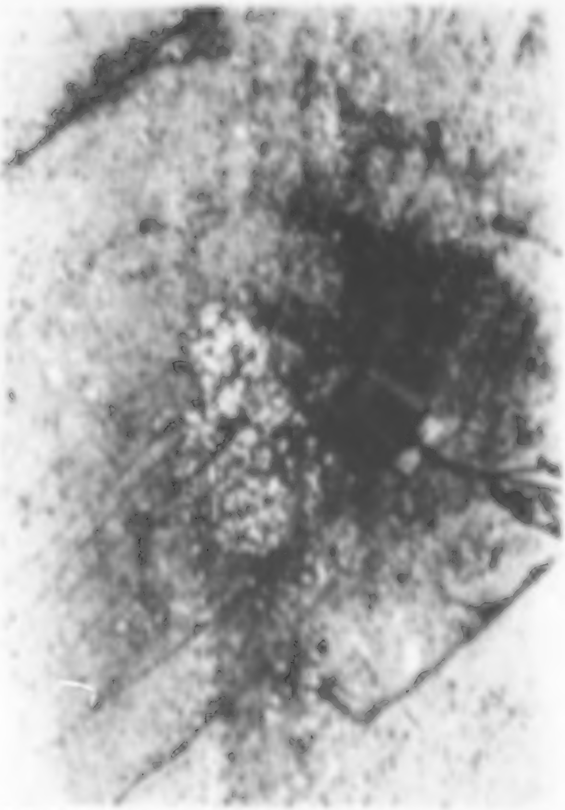

Plate 6. *Close-up of phyric–aphyric banding, locality 88. Note accompanying glomeroporphyritic texture.*

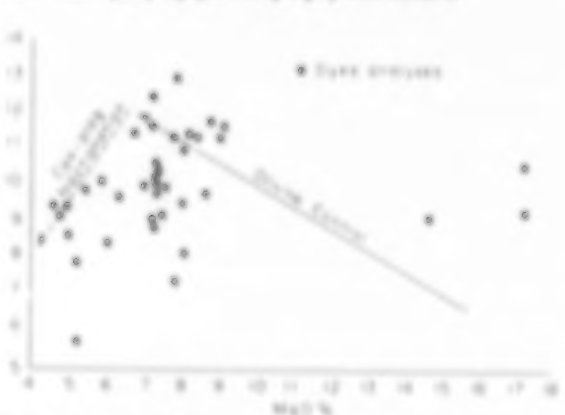

Figure 3. *Plot of CaO percent against MgO percent for dyke margins and centres of the Kikkertavak swarm. The cpx-plagioclase fractionation path is for the Karoo–Deccan flood basalts, after Cox (1980) and Cox and Hawkesworth (1985).*

1980; Cox and Hawkesworth, 1985), which show broadly similar trends. A clinopyroxene–plagioclase fractionation path drawn for the Kikkertavak dykes would run parallel to the trend of the Karoo magma, but the increase in calcium content from picrites to non-picrites, during olivine fractionation, is much less pronounced for the Kikkertavak dykes than for the Deccan flood basalts.

The plot of potash versus silica (Figure 4) shows a dominantly subalkalic composition. At present, there is little evidence for LILE-enriched heterogeneous sources for the Kikkertavak magmas, which tend to produce vertical plots of potash versus silica (Cox, 1980); the broadly positive correlation between potash and silica can be explained by fractional crystallization or by crustal contamination of the magma.

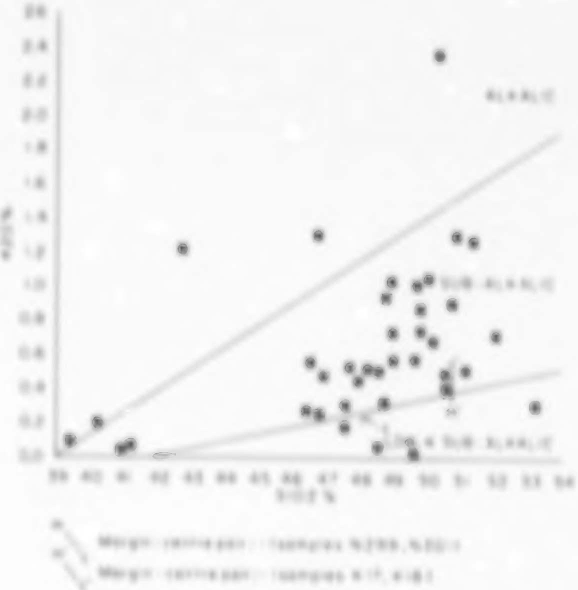

Figure 4. *Plot of K_2O percent vs SiO_2 percent. Field boundaries extrapolated from Middlemost (1975).*

There is no evidence at this crustal level to suggest that contamination from either the partial melting of wallrock or from bulk rock assimilation resulting from the entrainment and melting of xenoliths has occurred; margin-centre pair samples taken from the same dykes (Figure 4) do not show large differences in potassium content. Also xenoliths are rare and, where present, are singular and confined to dyke margins. These are certainly detached bridges formed by the linkage of *en echelon* crack arrays in the initial stages of dyke formation (Nicholson and Pollard, 1985). At only one place is an abundance of xenoliths observed, where 60 percent of a diabase dyke, which rapidly dies out upward, consists of tabular xenoliths, many of which are exotic and different from the granodioritic host rock. It has been argued previously that their presence and orientation are due to horizontal magma flow (Cadman, 1989) but, alternatively, they may represent detached host-rock bridges that were easily entrained by the magma due to their low density and that accumulated at the roof of the dyke. The dyke has chilled margins adjacent to the xenoliths, none of which have undergone any absorption; consequently the magma was not superheated when it entrained the xenoliths and did not contain the heat supply to melt them. Primary dyke-wallrock contacts are always sharp with chilled, sometimes glassy, margins but with no observed baking or induced ductility in the country rock. These features suggest that the country rock was relatively cold at the time of intrusion, which helps to explain the resistance to melting.

MAGMA FLOW AND DIFFERENTIATION

FLOW DIRECTION

The direction of magma flow in dykes has implications for the emplacement, structure and geochemical evolution of dyke swarms. The Kikkertavak dykes are predominantly vertical features throughout the Hopedale Block, therefore, it seems likely that no crustal tilting or deformation has occurred. Hence, studies of the primary flow directions in the dykes are possible.

Field relationships suggest a dominantly vertical flow direction for both the Kikkertavak and Harp dyke swarms. Dykes die out laterally, and isolated diabase veins injected into propagating *en échelon* crack arrays are common on horizontal surfaces but do not occur on vertical ones; at least a component of vertical magma flow is required to produce such field relationships. The study of crystal alignment in thin section was not successful; phenocrysts stuck on dyke margins are randomly orientated and did not yield any paleoflow information.

MAGMA DIFFERENTIATION

Diabase dykes in the Kikkertavak swarm are locally highly differentiated in terms of phenocryst content (Cadman, 1989). This is a function of flow processes acting on a previously homogeneous magma. Two cases have been found of differentiated material consisting of a massive plagioclase ultraphyric dyke core surrounded by aphyric to subphyric diabase (Plate 2). This structure suggests flow differentiation of material (Komar, 1972), with concentration of large, megaphyric material into the fast-flowing central portion of the dyke. Composite intrusion of aphyric and phyric magma batches is an alternative explanation, but chilling of phyric cores against aphyric margins was not seen. More commonly, dyke structure consists of thin, alternating layers of aphyric and phyric material either in the margins or the centres of dykes (Plate 3). This structure cannot be explained by flow differentiation or composite intrusion and is more likely to result from the differential accretion of phenocrysts onto the inward-advancing solid-liquid interface within the dyke. The degree of phenocryst accretion changes with time due to hydraulic changes in magma flow (Platten and Watterson, 1987). In contrast, the Harp dykes are always homogeneous and highly phyric, and do not contain megaphyric differentiation structures.

The end result of the differentiation processes is that no part of a dyke (and hence no sample) is representative of the magma composition that flowed through it. Thus, the differentiation processes are superimposed on the clinopyroxene (± plagioclase) fractionation shown in Figure 3. (It is also possible that some 'Kikkertavak' samples are mis-identified Harp dykes, which may produce the same effect.) The effect plagioclase differentiation has on the data is shown in Figures 5 and 6. In the most extreme theoretical case of plagioclase differentiation, part of the dyke becomes pure plagioclase. Taking the simplistic case of pure anorthite, this would lead to an oxide composition of 25 percent CaO, 25 percent Al_2O_3 and 50 percent SiO_2. (The central portion of the dyke shown in Plate 2 attained a value of 88 percent plagioclase, 80 percent as megacrysts and about 8 percent as groundmass.) Hence, portions of any original plagioclase-phyric magma in a differentiated Kikkertavak dyke will trend toward these oxide values if enriched in plagioclase phenocrysts or away from it, if depleted. Examples of such trend lines are shown in the CaO:MgO plot in Figure 5. Figure 6 shows an expanded part of Figure 5, with margin-centre and margin-margin sample pairs, taken from dyke centres and margins at the same locality. There is little difference between samples in margin-margin pairs, which is to be expected in vertical dykes such as the Kikkertavak swarm as there is no gravity component favouring the settling (or floating) of phases preferentially at one margin relative to the other. However, one margin-centre pair shows a wide disparity in oxide values and gives a trend line parallel to the anorthite depletion/enrichment trend. If the effect of ongoing magma evolution during the period between solidification of marginal and central portions of the dyke is discounted, original oxide values for the undifferentiated magma will plot somewhere on the line between the plagioclase-depleted margin and the plagioclase-enriched centre. The same margin-centre pair is plotted in Figure 7 for alkali index versus alumina. Again, there is considerable difference in Al_2O_3 enrichment between the samples as aluminum is a major component of anorthite. Such high alumina values as that yielded by the dyke centre sample, are rare in continental flood basalts and consequently other high values plotted here may be the result of plagioclase differentiation and enrichment from originally tholeiitic melts. Another margin-centre pair plotted in Figure 6 shows little disparity in oxide values and hence differentiation does not operate in all dykes. (Aphyric magmas, for example, obviously cannot be differentiated in terms of phenocryst content). Thus, the feldspar differentiation process blurs the calcium–magnesium correlation shown in Figures 3 and 5.

At the end of the differentiation processes, portions of the dyke become variably enriched or depleted in phenocrystic content, hence affecting the observed geochemistry. Given the large abundance of plagioclase phenocrysts and megacrysts in some Kikkertavak dykes and the lack of pyroxene phenocrysts of similar size, it would seem more likely that plagioclase, not pyroxene, is the main fractionating phase. However, although the concentration of plagioclase phenocrysts is locally very high, the amount of material possessing this texture is volumetrically small, for example, differentiated structures are not seen in the gabbroic parts of dykes, with the exception of the highly flow differentiated gabbro in Plate 2, and plagioclase megacrysts are also very rare.

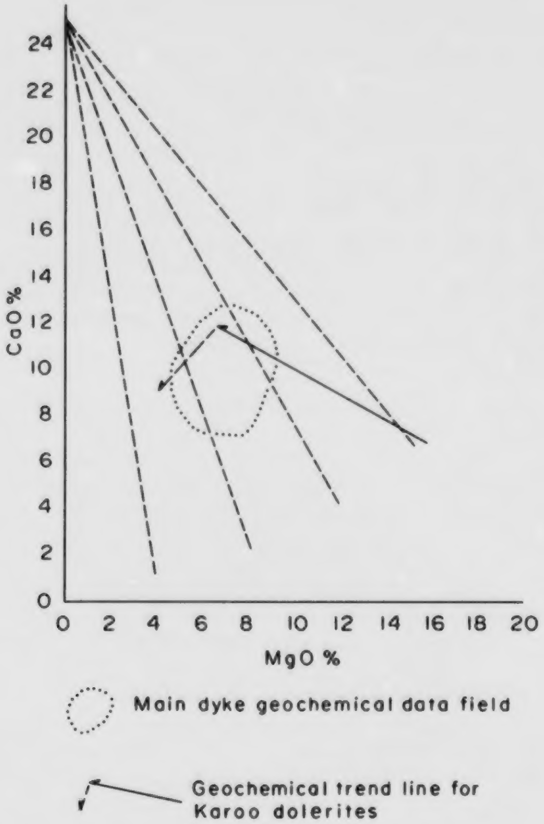

Figure 5. *Plot of CaO percent vs MgO percent showing paths of magma evolution due to differentiation of anorthite. Fractionation path for Karoo–Deccan flood basalts from Cox (1980) and Cox and Hawksworth (1985).*

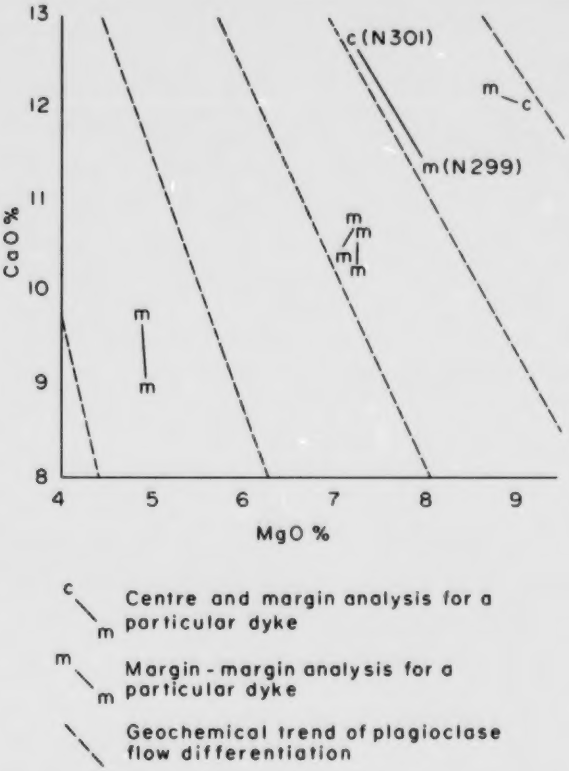

Figure 6. *Expanded section of Figure 5, showing margin-margin and margin-centre pairs from Kikkertavak dykes and their relationships to plagioclase (anorthite) differentiation.*

The fine-grained margins of one Kikkertavak gabbro dyke possess very pronounced phyric–aphyric layering, including plagioclase megacrysts up to 5 cm long. This differential accretion structure ceased abruptly within 3 m of either margin, passing into >30 m of homogeneous gabbro, but without chilling of the gabbro against the marginal diabase.

Another example of the composite structure is shown in Figure 8 and Plates 3 to 6 of a Kikkertavak diabase dyke. The dyke contains a 2-m-wide aphyric margin, which is followed by a 1-m-wide 'phyric' zone of thin, alternating, phyric and aphyric layers (Plates 3 and 4) before reverting to aphyric diabase for a farther 2 to 3 m centreward. The 'phyric' zone is associated with differential accretion (Platten and Watterson, 1987). Inward from here, the structure of the dyke changes abruptly. Distinct, highly irregular bands could be traced along the length of the dyke (Plate 5). Commonly they are accompanied by thin, gabbroic cumulates (Plate 6), which quickly fade out centreward into aphyric or subphyric diabase. The bands and their associated gabbroic layers commonly thin rapidly and fade laterally, or are truncated by other bands and lunate trough structures. At other localities in the same dyke, large gabbroic xenoliths are found within the irregularly layered, central section of the dyke.

The structures in this dyke are interpreted in terms of variable flow regimes. The differential accretion structure found on both margins of this dyke suggests that originally, the margins formed a thin diabase dyke that expanded during flow to some 6 m in final width. The thin, margin parallel, laterally persistent, phyric–aphyric layering suggests low magma flow rates since features such as scouring or truncations are absent. The dyke then dilated abruptly, and the magma flow became faster, forming the inner 3-m-thick aphyric zone. Flow then became increasingly turbulent: each successive irregular layer in this dyke represents the deposits of a turbulent current, commonly scouring and eroding previously deposited layers. Size-grading of deposited crystal material resulted in the thin gabbroic cumulates seen at the start of many layers, and cognate xenoliths of gabbroic material were ripped up and deposited in the central core of the diabase dyke. The presence of these size-graded cumulates is proof that at least some shallow-level fractionation by sidewall accretion did occur in the dyke system. However, it is not likely that the required amount of material to produce the observed fractionation trends (Figures 3 and 4) could be removed from the liquid by sidewall accretion alone, given the limited widths of the dykes. Thompson (1974) shows that

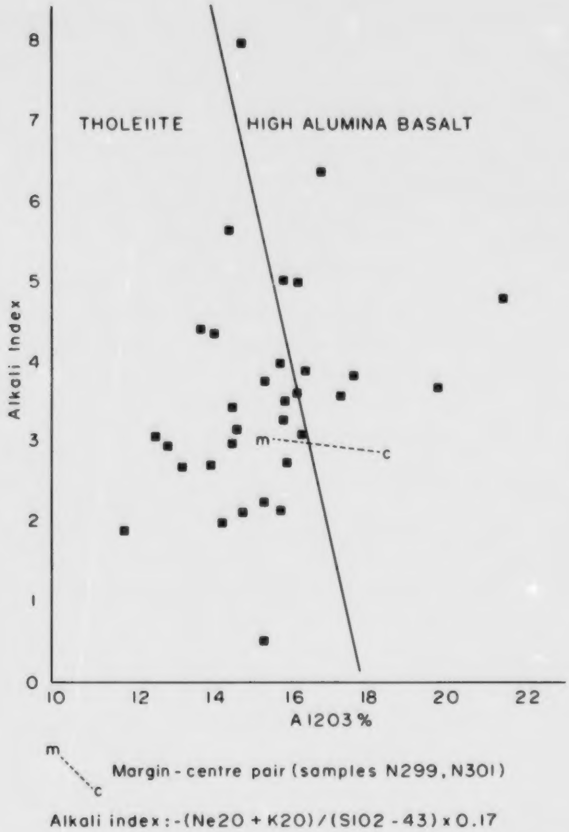

Figure 7. *Plot of alkali index vs Al_2O_3 percent. Tholeiite–high-alumina basalt boundary from Middlemost (1975).*

high pressure crystallization (and thus fractionation) of plagioclase and pyroxene is also possible. In the absence of suitable high-level magma chambers in the Hopedale Block or neighbouring terranes, it is more likely that much of the fractionation took place at deeper levels, perhaps in moho-based magma chambers.

PETROLOGICAL MODEL

The structures described above and the presence of cognate gabbroic xenoliths within Kikkertavak diabases suggest that the gabbros and diabases are both evolved from the same plagioclase megacrystic–phenocrystic magmas, the diabases forming the thinned vertical extensions of underlying gabbros. Upward thinning of Proterozoic dykes is also postulated for the Scourie dyke swarm in northwest Scotland (Tarney and Weaver, 1987). The differences in petrology can be explained by changes in flow regime. The large low-density, plagioclase megacrysts are easily entrained in the upwardly flowing magma. The heavy concentration of plagioclase megacrysts in a handful of dykes rather than uniformly throughout the whole swarm suggests their sidewall accretion in 'blind chutes' or blocked fissures. These were progressively bypassed by the main magma flows represented by the large, homogeneous gabbros, which probably fed surface flood basalts. As flow was diverted to these wider fissures, phenocrysts and megacrysts were accreted to the cooling margins of the narrower, slower flowing dyke segments, forming the differentially accreted texture previously described. Judging by their rarity in large volumes of gabbroic rock, the plagioclase megacrysts probably form a very small overall percentage of the original magma, but become super-concentrated in a small number of dykes. As more phenocrystic material was deposited, the remaining magmas ceased first to be megaphyric and then gradually became aphyric. Therefore, the thinnest diabases are commonly aphyric as they represent the last magmas to crystallize before stagnation of a particular flow occurred.

Build up of magma pressure beneath blocked or partially blocked fissures seems to have led to their redilation and consequent catastrophic increase in magma flow energy levels through the intrusion, resulting in the scouring textures associated with the deposition of gabbroic cumulates shown in Figure 6 and Plate 6.

DYKE EMPLACEMENT AND STRUCTURE

The absence of an extensive deformation after the emplacement of the Kikkertavak dyke swarm in the Hopedale Block, together with excellent exposure, allows the study of primary dyke geometry, except for those Kikkertavak dykes near the Kanairiktok shear zone, in which dyke margins become deformed. Kikkertavak and Harp dykes are always rectiplanar except for some slightly irregular larger gabbros in both swarms. Lack of stoping, and sharp dyke-wallrock contacts indicate that each swarm was injected into a cold, brittle, upper crustal environment under neutral or tensional stress fields, which readily accommodated dilation.

On an outcrop scale, evidence for the exploitation of pre-intrusive anisotropies in the host rock (for example, joints and foliation) is very rare in the map area: dykes always crosscut foliation and no correlation exists between dyke width and the degree of parallelism to planar fabrics in the host gneisses. *En echelon* crack arrays are always developed and the associated features (bayonets and steps) are very commonly preserved in dyke margins. Exploitation of local anisotropies may be expected where magmatic pressure exceeds the compressive stress acting perpendicular to the plane of the anisotropy (Delaney *et al.*, 1986). Although the angle between the foliation and the strike of the crack arrays and dykes was commonly acute, this does not occur here; probably because the foliation is locally variable in trend and, despite the regional consistency of both the Fiordian and Hopedalian trends, rarely forms long-range, planar features. It is inefficient for an extensive rectiplanar body such as a dyke to exploit local crustal anisotropies as it would constantly have to accommodate local variations in trend. The only exceptions to this are minor Kikkertavak dykes conformably intruding Hopedalian-trending gneisses near Hopedale village, where straight planar foliations are sometimes developed (see Figure 2 and Plate 1).

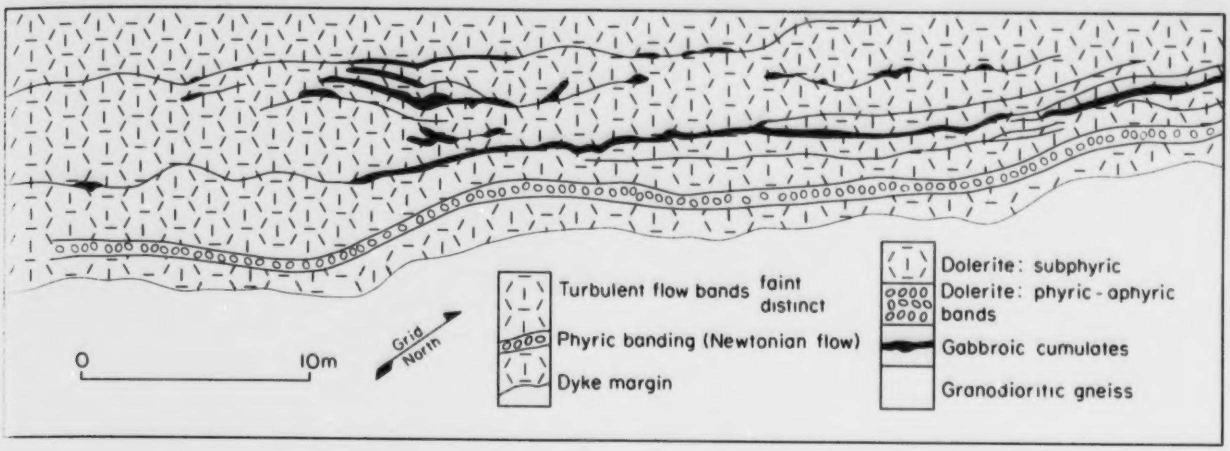

Figure 8. *Baseline-survey of flow structures in Kikkertavak diabase.*

Plate 5. *Transition of flow regime: the photograph shows the marginal phyric–aphyric banding texture (left) and its transition to a more turbulent flow regime, marked by the dark, lateral bands of gabbroic material (centre and right). Note the irregularity of these bands compared to the phyric–aphyric layering on the left.*

Plate 6. *Close up of a gabbroic band within sub-phyric diabase. Note that the plagioclase phenocrysts are dispersed rather than layered in the diabase.*

The Kikkertavak and Harp gabbros could easily be distinguished on the basis of trend; on a regional scale, there is a very strong correlation between the Fiordian trend and the trend of the Harp dyke swarm (Ermanovics and Raudsepp, 1979), particularly in the case of the large northeast-southwest-trending Harp gabbros. This suggests that crustal anisotropy is progressively more important for the larger intrusions as they are increasingly unaffected by local variations in foliation. However, Harp gabbros injected into Hopedale-trend gneiss continue to follow the Fiordian trend, suggesting that their paths of ascent were controlled either by a deeper Fiordian anisotropy or by a stress system coincident with the Fiordian trend. The gabbros of the Kikkertavak dyke swarm trend north-northeast–south-southwest and hence crosscut both Hopedalian and Fiordian fabrics and consequently may have a purely tectonic control. Smaller dykes, particularly in the Kikkertavak dyke swarm, do not conform to a uniform trend. However, since local anisotropies are not exploited, the orientation of the dykes must be controlled by the stress systems acting on the Hopedale Block at a regional or local level.

To see if individual dyke dilation directions could be related to a regional stress field, the horizontal dilation vector of Kikkertavak dykes sampled at random points in the field area was plotted against their strike. The plot (Figure 9) shows a very wide spread, not only of the orientation and dilation direction but also of the type of host-rock failure. Also plotted on the diagram is similar data for a local Kikkertavak dyke complex that shows almost as much variation as the regional data. The wide spread of regional data could perhaps be interpreted as variation in a regional, stress-induced pattern. However, intensive measurements of dilation and orientation data taken over 400 m of co-intrusive Kikkertavak dykes show almost as much scatter as the regional data. Therefore, the dilation and orientation of dykes is controlled by very local conditions.

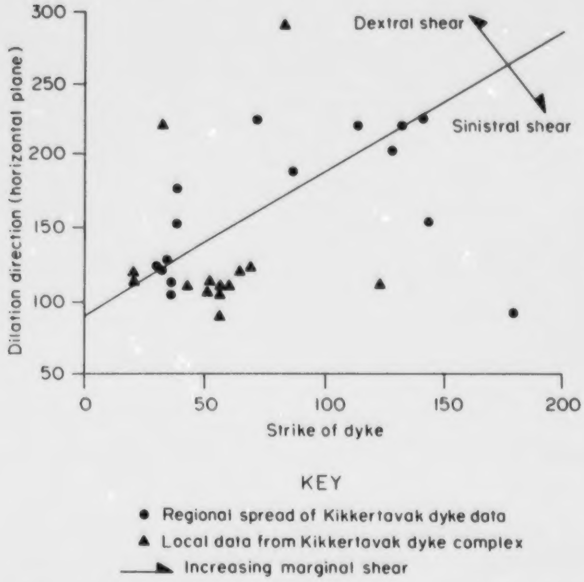

Figure 9. *Plot of the dilation vector in the horizontal plane versus the strike for randomly sampled Kikkertavak dykes and a local Kikkertavak dyke complex in the Hopedale Block.*

To see if the same is true for the Harp dykes, the dilation direction in the horizontal plane and orientation of three adjacent dykes at one locality were measured every 2 m along their length. The spread of data shown in Figure 10 shows again that dilation directions are extremely variable and thus, that these measurements cannot be used to infer the direction of the regional stress system operating at the time of intrusion.

The simplest dyke shown in Figure 10, dyke 2, shows up to 40° variation in both strike and direction of dilation. In places, dilation direction is orthogonal to the strike orientation of the dyke, i.e., the dyke opened by purely tensile failure. Other measurements, however, show varying amounts of dextral shear displacement have taken place on one margin relative to another during opening.

Dykes 1 and 3 show a larger spread of data due to their greater complexity: both dykes split into two branches, which act as conjugate shears. Thus, on the initial opening of the dyke, the branches dilate with opposing senses of shear displacement, which when summed cancel each other out, giving a more orthogonal opening direction over the whole system, as shown in Figure 11.

Even if these affects are accounted for, the three occupy quite different areas of the diagram. Thus, it appears that no overall common opening direction can be found for different dykes intruded in one outcrop. It is possible that the dykes were intruded at different times and that the local stress system had changed, or that the dykes opened synchronously and affected each others dilation and orientation by changing the local stress field.

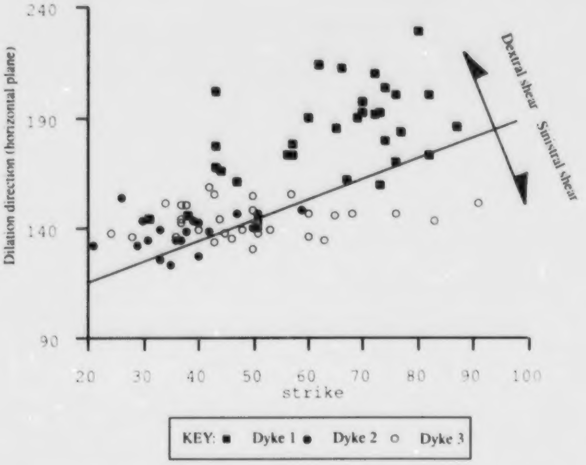

Figure 10. *Shows dilation direction as strike data for three closely spaced Harp dykes at the same locality. Each data point represents the strike and dilation direction of the dyke at a particular point along its length. Note that each dyke shows a wide scatter but occupies a different field on the diagram.*

The conclusion reached is that local dilation directions cannot in general be used to determine the dilation direction of the swarm as a whole unless very large numbers of dilation directions are summed, and that the map pattern of the larger dykes is probably the best guide to the regional stress direction. Since the local data does not suggest any consistent sense of transtensional shear, the overall dilation direction vector is therefore likely to be orthogonal to the trend of the largest dykes.

There is little information concerning dilation in the vertical plane, primarily due to the absence of good vertical outcrop. However, where suitable outcrops are present, dykes are usually vertical and have no component of dilation in this direction.

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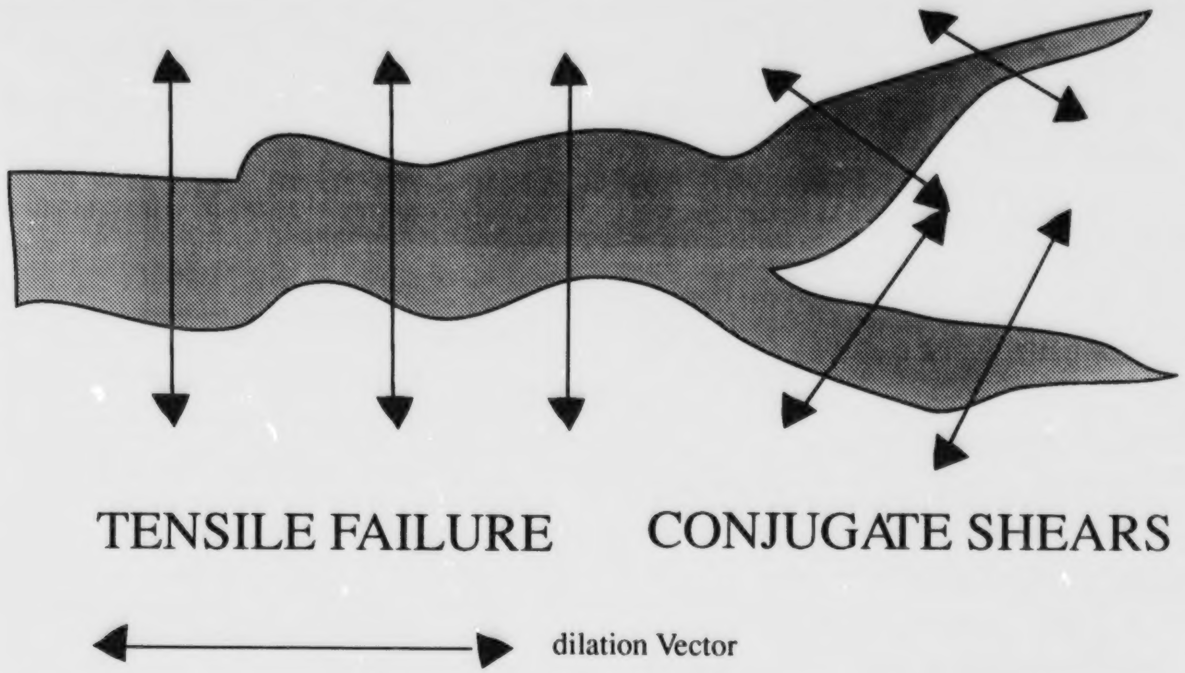

Figure 11. *Theoretical diagram showing the splitting of a dyke into two branches. The two branches of the dyke show very different directions and orientations to the single section of the dyke, which shows dilation at right angles to the orientation of the dyke. However, the sum of the dilation vectors, namely the direction of dilation and its magnitude (i.e., the width of the dyke) is the same as the dilation vector for the unsplit section. Similarly, individual dykes intruded synchronously may interact with each other so that, although showing markedly different dilation directions, the sum of the dilation directions shows a consistent opening direction.*

REFERENCES

Cadman, A.
1989: The petrogenesis and emplacement of Proterozoic dyke swarms, Part 1: initial findings and paths of further research. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 1-7.

Cox, K.G.
1980: A model for flood basalt volcanism. Journal of Petrology, Volume 21, pages 629-650.

Cox, K.G. and Hawksworth, C.J.
1985: Geochemical stratigraphy of the Deccan Traps, at Mahabaleshwar, Western Ghats, India, with implications for open system magmatic processes. Journal of Petrology, Volume 26, pages 355-377.

Delaney, P.T., Pollard, D.D., Ziony, J.I. and McKee, E.H.
1986: Field relationships between dikes and joints: emplacement processes and paleostress analysis. Journal of Geophysical Research, Volume 91, Number B5, pages 4920-4938.

Ermanovics, I.F.
1979: Geology, Adlatok Bay–Florence Lake area, Labrador. Geological Survey of Canada, Open File 580.

1980: Geology of the Hopedale Block of Nain Province, Labrador: Report 2. *In* Current Research, Part B. Geological Survey of Canada, Paper 80-1B, pages 11-15.

1981a: Geology, Ingrid Group map-area, Newfoundland (13N/5). Geological Survey of Canada, Open File 755.

1981b: Geology, Hunt River map-area, Labrador, Newfoundland (parts of 13N/7,9,10,15,16). Geological Survey of Canada, Open File 778.

1984: Geology of the Hopedale Block, Labrador, Newfoundland (NTS 13N/1,2,3,5,6,7,8 and 13O/4,5). Geological Survey of Canada, Open File 1083, Map 2, 1:100,000 scale.

Ermanovics, I. and Raudsepp, M.
1979: Geology of the Hopedale Block of eastern Nain Province, Labrador: Report 1. *In* Current Research, Part B. Geological Survey of Canada, Paper 79-1B, pages 341-348.

Ermanovics, I. and Korstgaard, J.A.
1981: Geology of the Hopedale Block and adjacent areas, Labrador: Report 3. *In* Current Research, Part A. Geological Survey of Canada, Paper 81-1A, pages 69-76.

Ermanovics, I.F., Korstgaard, J.A. and Bridgwater, D.
1982: Structural and lithological chronology of the Archean Hopedale Block and the adjacent Proterozoic Makkovik Subprovince, Labrador: Report 4. *In* Current Research, Part B. Geological Survey of Canada, Paper 82-1B, pages 153-165.

Grant, N.K., Voner, F.R., Marzano, M.S., Hickman, M.H. and Ermanovics, I.F.
1983: A summary of Rb−Sr isotope studies in the Archean Hopedale Block and the adjacent Proterozoic Makkovik Subprovince, Labrador: Report 5. *In* Current Research, Part B. Geological Survey of Canada, Paper 83-1B, pages 127-134.

Huppert, H.E. and Sparks, R.S.J.
1985: Cooling and contamination of mafic and ultramafic magmas during ascent through the continental crust. Earth and Planetary Science Letters, Volume 74, pages 371-386.

Komar, P.D.
1972: Flow differentiation in igneous dikes and sills: profiles of velocity and phenocryst concentration. Geological Society of America Bulletin, Volume 83, pages 3443-3448.

Korstgaard, J.A. and Ermanovics, I.
1984: Archean and early Proterozoic tectonics of the Hopedale Block, Labrador, Canada. *In* Precambrian Tectonics Illustrated. *Edited by* A. Kröner and R. Greiling. E. Schweizerbartsche Verlagsbuchhandlung (Nägele u. Obermiller), Stuttgart, pages 295-318.

Loveridge, W.D., Ermanovics, I.F. and Sullivan, R.W.
1987: U−Pb ages on zircon from the Maggo Gneiss, the Kanairiktok Plutonic Suite and the Island Harbour Plutonic Suite, coast of Labrador, Newfoundland. *In* Radiogenic Age and Isotope Studies: Report 1. Geological Survey of Canada, Paper 87-2, pages 59-65.

Meyers, R.E. and Emslie, R.F.
1977: The Harp Dykes and their relationship to the Helikian geological record in central Labrador. Canadian Journal of Earth Sciences, Volume 14, pages 2683-2696.

Middlemost, E.A.K.
1975: The basalt clan. Earth Science Reviews, Volume 11, pages 337-364.

Nicholson, R. and Pollard, D.D.
1985: Dilation and linkage of en-echelon cracks. Journal of Structural Geology, Volume 7, pages 583-590.

Platten, I.M. and Watterson, J.
1987: Magma flow and crystallization in dyke fissures. *In* Mafic Dyke Swarms. *Edited by* H.C. Halls and W.F. Fahrig. Geological Association of Canada, Special Paper 34, pages 65-73.

Sutton, J.S., Marten, B.E., Clark, A.M.S. and Knight, I.
1972: Correlation of the Precambrian supracrustal rocks of coastal Labrador and southwestern Greenland. Nature, Physical Science, Volume 238, pages 122-123.

Tarney, J. and Weaver, B.L.
1987: Geochemistry and petrogenesis of Early Proterozoic dyke swarms. *In* Mafic Dyke Swarms. *Edited by* H.C. Halls and W.F. Fahrig. Geological Association of Canada, Special Paper 34, pages 81-94.

Taylor, F.C.
1971: A revision of Precambrian structural provinces in northeastern Quebec and northern Labrador. Canadian Journal of Earth Sciences, Volume 8, pages 579-584.

Thompson, R.N.
1974: Primary basalts and magma genesis. 1: Skye, northwest Scotland. Contributions to Mineralogy and Petrology, Volume 45, pages 317-341.

*Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 191-204*

THE PETROGENESIS AND EMPLACEMENT OF PROTEROZOIC DYKE SWARMS, PART 3: GEOCHEMISTRY AND MAGMATIC EVOLUTION OF THE MAFIC DYKE SWARMS OF THE HOPEDALE BLOCK, LABRADOR

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ABSTRACT

The Kikkertavak and Harp dykes of the Archean Hopedale block, Labrador, show remarkable similarities in their geochemical evolution, despite some striking differences in petrographic textures and the 1 Ga interlude between the intrusion of the two swarms. The differing textural features and field orientations of the dykes suggest injection of the swarms within different tectonic environments, whereas the geochemical similarities between these and other Proterozoic swarms suggest a cyclicity, unconnected with orogenic crust-forming events in the Hopedale block or elsewhere. Study of these dykes may therefore yield information concerning the formation of dyke swarms in the Proterozoic and the usefulness of Phanerozoic models in contributing to their understanding.

INTRODUCTION

Proterozoic dyke swarms are an important component of Precambrian magmatism. Much debate has focussed on the applicability of Phanerozoic models of intrusion versus arguments that uniquely Precambrian processes are necessary to explain their formation. They provide clues to processes of magma evolution and also the nature of the tapped mantle sources and their secular change, if any, with time. Proterozoic dyke swarms may require more than one mechanism of intrusion, or more than one variant of tectonic style to explain their formation. Examples of such swarms include the Early Proterozoic Kikkertavak and Middle Proterozoic Harp dyke swarms, which intrude the Archean Hopedale block. The existence of these two swarms allow changes and developments in mantle source characteristics, tectonics and magmatic styles to be assessed over the period of their intrusion.

PREVIOUS WORK

In recent years, attempts have been made, as part of IGCP project no. 257, to research Proterozoic dyke swarms in the context of earth evolution. Little detailed research has been done on either of the dyke swarms in the Hopedale block. Previous Kikkertavak data consists solely of analyses undertaken by the Geological Survey of Canada (GSC) during a regional 1:100,000-scale mapping project (Ermanovics, *in press*). However, the Harp swarm has been investigated in the area around the Harp Lake anorthosite–gabbro plutonic complex approximately 100 km west of the Hopedale block by Meyers and Emslie (1977).

The evolutionary history of the Archean gneisses that make up the Hopedale block was studied during the GSC program (Ermanovics, 1979, 1980, 1981a, b, 1984; Ermanovics and Raudsepp, 1979; Ermanovics and Korstgaard, 1981; Ermanovics *et al.*, 1982; Ermanovics, *in press*). Earlier work has also concentrated on structural and metamorphic histories (e.g., Taylor, 1971) and correlation with similar terranes in West Greenland (e.g., Sutton *et al.*, 1972).

GEOLOGICAL SETTING OF THE DYKE SWARMS

The Hopedale block lies in the southern part of the Nain Province, bounded by the Churchill Province in the west and the Makkovik Province in the southeast (Figures 1 and 2). It consists of polydeformed, mainly granodioritic to tonalitic gneisses that have a predominantly northeast-southwest (Fiordian) trend. The Fiordian-trending fabrics are interpreted by Ermanovics *et al.* (1982) to be late Archean and postdate the granitoid rocks of the Kanairiktok Intrusive Suite, dated at about 2830 Ma (U–Pb zircon concordia, Loveridge *et al.*, 1987). The Fiordian trend overprints an earlier northwest-southeast (Hopedalian) trend, which was probably developed between 3250 and 3000 Ma (Grant *et al.*, 1983; Loveridge *et al.*, 1987). Within both the Fiordian and Hopedalian domains, subvertical planar and linear fabrics show strong parallelism, suggesting block-wide, shear-zone deformation in both cases. The Fiordian-trending gneisses, which dominate the study area, are deformed agmatitic gneisses having some amphibolite bands. The gneisses are at amphibolite facies, possibly retrogressed from a granulite-facies assemblage. Any very early Archean structural and metamorphic histories were largely erased by the Hopedalian event (Ermanovics *et al.*, 1982).

Fiordian structural trends are truncated by diabase dykes forming sub-rectiplanar intrusions from 1 cm to 100 m in

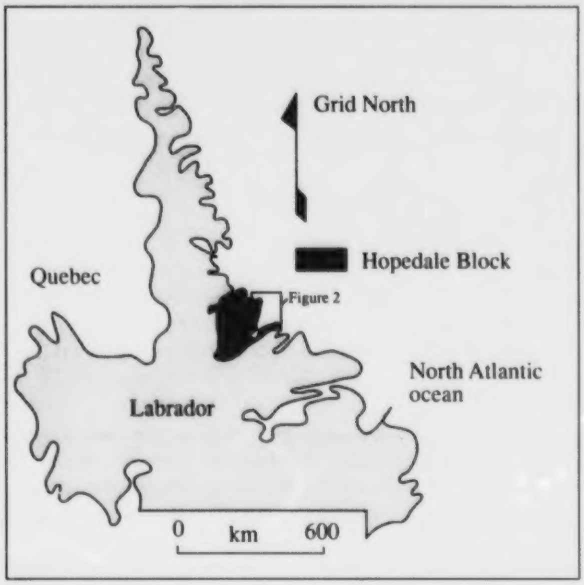

Figure 1. *Location of the Hopedale block, Labrador.*

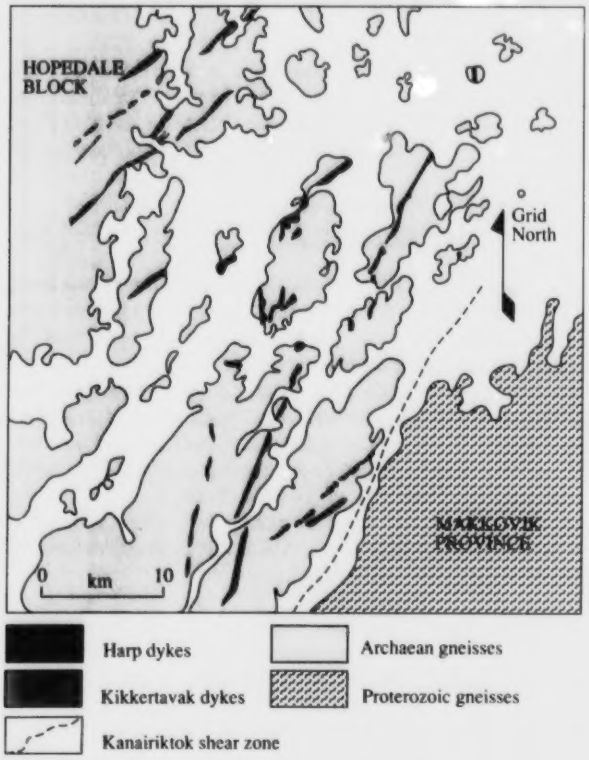

Figure 2. *Map of the coastal region of the Hopedale block, Labrador, showing gabbroic dykes of the Kikkertavak and Harp dyke swarms. (Adapted from Ermanovics, 1979, 1981b and 1984)*

width. Dykes of the Kikkertavak swarm have no consistent orientation except for the larger gabbro bodies (>20 m width), which trend north to northeast. The Harp dykes have a strong northeast-southwest orientation (parallel to the Fiordian trend) irrespective of dyke width. Dykes of both swarms are only locally concordant with the gneissic foliation where planar fabrics are especially well developed (Cadman, *this volume*).

Neither the Kikkertavak nor Harp dykes show any evidence of post-intrusion reorientation by crustal folding or tilting, but shearing and low-grade alteration does affect dykes of the Kikkertavak swarm toward the Kanairiktok shear zone, which forms the boundary between the Hopedale block and the Proterozoic Makkovik Province. The Kikkertavak dykes are dated at ca. 2200 Ma (Rb–Sr whole-rock data, B.J. Fryer, in Grant *et al.*, 1983) and the Harp dykes at ca. 1200 Ma, (Rb–Sr whole-rock data, F.R. Voner, in Ermanovics *et al.*, 1982; Grant *et al.*, 1983).

Two other periods of mafic dyke injection are present in the Hopedale block. The late Archean Hopedale dykes were deformed by the Fiordian event and now consist of amphibolite boudins and discontinuous bands. Dioritic and lamprophyric dykes, intruded ca. 1640 Ma and termed the Kokkovik intrusions, are found rarely throughout the Hopedale block, with small sills present in the west of the area. Both dyke groups are volumetrically minor compared to the Kikkertavak and Harp swarms and are not discussed here.

CLASSIFICATION OF THE DYKE SWARMS

Geochemically, the Proterozoic dyke swarms of the Hopedale block can be divided into three types: tholeiitic basalts, high-magnesian–low-iron dykes, and high-magnesian–high-iron dykes. Tholeiitic magmas form the vast majority of intrusions in both the Kikkertavak and Harp dyke swarms.

The largely unaltered post-Fiordian rectiplanar intrusions, which make up the bulk of the dykes in the area, were first mapped solely as 'Kikkertavak' dykes and then reclassified on the basis of petrography as being either altered diabasic or gabbroic dykes with a simple gabbroic mineralogy (Kikkertavak) or fresh olivine-bearing diabases–gabbros having affinities to the Harp dykes (Ermanovics and Raudsepp, 1979; Ermanovics *et al.*, 1982) described from around the Harp Lake intrusive complex (Meyers and Emslie, 1977).

THE KIKKERTAVAK DYKES

Petrographically, the Kikkertavak dykes are classified as containing clinopyroxene, plagioclase (labradorite), magnetite, ilmenite and secondary hornblende, rare biotite, quartz and myrmekitic alkali feldspar (Ermanovics, *in press*). The labradorite forms an ophitic to subophitic texture with clinopyroxene, is commonly zoned and locally consists of partially resorbed cores surrounded by euhedral-zoned overgrowths. Alteration of feldspar to sericite, especially in crystal cores, is ubiquitous in the Kikkertavak dykes. Opaque minerals also show common crystal zoning from titanium-rich cores to magnetitic rims, whereas others show unzoned magnetite compositions.

Kikkertavak dykes are often plagioclase phyric and heavily zoned in terms of the volumetric abundance of phenocrysts across the width of the dyke: phenocrysts are commonly around 1 cm in length, zoned, euhedral and locally have glomeroporphyritic textures. In places, in highly differentiated dykes, plagioclase megacrysts up to 15 cm long are present in thin (< 3 m) phenocryst-rich margin-parallel zones. Microphenocrysts of clinopyroxene and plagioclase are also commonly present in thin sections of chilled margins. Other observed textural features included gabbroic cognate xenoliths. Xenoliths of country rock are rare within the dykes and where present consist of host-rock screens separated from the wall rock during the initial stages of dyke dilation.

THE HARP DYKES

The primary mineralogy of the Harp dykes consists of olivine, Ti-rich clinopyroxene, plagioclase (labradorite–andesine), magnetite, ilmenite and apatite (Ermanovics, *in press*). Dykes are rarely phyric and where present, plagioclase phenocrysts are sparse. Microphenocrysts of clinopyroxene, olivine and (most commonly) plagioclase are also common in thin sections of samples taken at chilled margins. The larger gabbroic Harp intrusions often contain patches of dioritic pegmatite (Ermanovics *et al.*, 1982) along with euhedral megacrysts of plagioclase, clinopyroxene and hornblende up to 10 cm in length.

DISCRIMINATION OF KIKKERTAVAK AND HARP SWARMS

Kikkertavak and Harp dykes have traditionally been discriminated on the basis of petrology and alteration textures (e.g., Ermanovics and Raudsepp, 1979). However, in practice, neither is a wholly satisfactory guide to swarm classification. Dykes of the Kikkertavak swarm frequently have brecciated, sheared or altered margins (Kranck, 1953; Ermanovics and Raudsepp, 1979) for distances of up to 20 km north of Kanairiktok Bay, probably as a consequence of Proterozoic tectonism along the Kanairiktok shear zone. The Late Proterozoic Harp dykes do not show this feature and thus, sheared margins are a confirmation of a Kikkertavak age. Associated alteration reaches amphibolite facies within 2 km of the Kanairiktok shear zone where feldspar is replaced by sericite, and clinopyroxene by hornblende, actinolite and uralitic amphiboles. At greater distances, clinopyroxene is unaltered except for the rare presence of secondary hornblendic rims on some crystals, whereas feldspar remains seriticized to variable degrees throughout the field area. Sericitic alteration is also common to a lesser extent in dykes classified as 'Harp' intrusions, and hence, cannot be used as a feature exclusive to Kikkertavak dykes.

Away from the Kanairiktok shear zone, a previous criteria for the classification of non-phyric dykes as belonging to the Harp swarm, namely the presence of olivine, is not always conclusive. In one major north-northeast-trending gabbroic dyke stretching from the mouth of Little Bay to the mouth of Kanairiktok Bay, accessory olivine is replaced by magnetite. Within 5 km of Kanairiktok Bay, alteration of plagioclase and clinopyroxene increases and olivine disappears as the shear zone is approached. To the north of this dyke, intrusions of similar size and orientation have the megacrystic texture characteristic of some Kikkertavak dykes. Hence, this olivine-bearing dyke is almost certainly of Kikkertavak age. The absence of olivine in southern portions of this dyke is probably due to the complete alteration of the mineral to serpentine. Similarly, in fresher intrusions classified as 'Harp dykes', olivine maybe completely pseudomorphed by serpentine whereas other minerals are left unaltered. In more highly altered dykes, such pseudomorphs become much more diffuse and as a consequence the parent mineral is dificult to identify. Therefore, the presence of olivine and degree of alteration maybe to some extent mutually dependent criteria unassociated with the primary petrological characteristics of the dyke magma.

The larger intrusions can be classified on the basis of their field trend: Kikkertavak gabbroic dykes and some thick (width > 10 m) diabases have a north to north-northeast trend, whereas the majority of gabbroic dykes (10 to 100 m in width) have consistent strikes of 050 to 060° that are characteristic of Harp dykes (Ermanovics and Raudsepp, 1979). Some smaller diabase dykes can also be classified as Harp on the basis of maintaining a consistent northeast trend. However, the wide variety of other orientations causes problems in classification unless they possess some of the other diagnostic features described above.

High-Magnesian–Low-Iron Dykes

Four picrite dykes were identified in the field area. One 20-m-wide dyke, 5 km northwest of the Kanairiktok shear zone has well-developed actinolitic rims on clinopyroxenes and a sheared margin characteristic of some Kikkertavak dykes. The primary mineralogy consists of olivine, clinopyroxene, plagioclase and opaques. These dykes also show a high degree of alteration: olivine is commonly 60 to 100 percent replaced and pseudomorphed by serpentine; clinopyroxene is replaced by hornblende, actinolite and uralite; and plagioclase is replaced by sericite.

Another picrite dyke, 10 km northwest of the Kanairiktok shear zone on Kikkertavak Island, displays well-developed crenulated fabrics, complete alteration of the original mineralogy, and contains few remaining pseudomorphs. Two other picrites 20 km northwest of the shear zone show similar alteration states. These latter three picrites are laterally impersistent, narrow (< 5 m) and have a deep green colouration. This degree of alteration well away from the Kanairiktok shear zone is probably a consequence of the susceptibility of serpentine to deformation, rather than to a higher metamorphic grade having been attained by these dykes in comparison to altered tholeiitic intrusions.

High-Iron–High-Magnesian Dykes

Two dykes in the field area have this unique geochemistry and are very distinct from the dykes discussed above. They appear black and fresh both in the field and in thin section, and therefore, are classed as members of the Harp swarm. One such dyke, striking 044°, contains 20 to 30 percent euhedral olivine phenocrysts largely altered to serpentine pseudomorphs. The groundmass consists of opaque phases, clinopyroxene and plagioclase, and the proportion of opaques is highest at the northwest margin (50 percent). Reaction rims are well developed against both the tonalitic country rock, and around partially resorbed olivine crystals that lie at the margin. Both reaction rims and resorption of the olivines decrease toward the centre of the dykes. The southeastern margin has a much coarser mineralogy, containing olivine (45 percent), plagioclase (45 percent) and opaques (10 percent) and lacking groundmass or evidence of reaction haloes in the crystals or against country rocks.

GEOCHEMISTRY

The geochemistry of the two dyke swarms is based on samples positively identified by the features discussed above as belonging to either the Kikkertavak or Harp swarm. The majority of the samples are at present unclassified and have therefore, not been used in the interpretation of the geochemistry.

The geochemistry of the Kikkertavak and Harp dyke swarms is summarized in a number of variation diagrams. Figures 3 to 8 are trace-element spidergrams and REE plots for the Kikkertavak dykes. Figures 9 to 12 show similar plots for the Harp dyke swarm. Figures 13 to 21 illustrate major-element versus trace-element variation diagrams for the Kikkertavak and Harp swarms. All samples are tholeiitic basalts unless otherwise stated.

CRYSTALLIZATION PROCESSES

Despite the petrographic differences between the tholeiitic dykes in the Kikkertavak and Harp swarms, their geochemistry shows many similarities. Both suites show good correlation between CaO percent and MgO percent (Figure 13), suggesting clinopyroxene–plagioclase fractionation. This trend is common to many flood basalt provinces: for example, Deccan Plateau basalts (e.g., Cox and Hawksworth, 1985), Karoo volcanics series (e.g., Cox, 1980, 1983) and Columbia River basalts (Basaltic Volcanism Study Project, 1981). The absence of olivine (except rarely in accessory amounts) in the Kikkertavak tholeiite dykes suggests that this phase is not likely to be involved in fractionation of the tholeiitic basalts.

The high-iron (Fe_2O_3) concentrations (total iron = 9.21 percent) reached by both Kikkertavak and Harp magmas point to plagioclase being the major crystallizing phase in the Labrador swarms. This is supported by the plagioclase megaphyric textures of some Kikkertavak dykes (Cadman, 1989) and the absence of any other phenocrystal phases. However, the Harp dykes show the development of an equally strong iron-enrichment pattern without the development of porphyritic textures.

The negative Sr anomaly seen in spidergrams for all dyke types discussed (Figures 3, 4, 9 and 10) could be due to derivation from a Sr depleted source, a consequence of plagioclase fractionation, or a mixture of both. Selected spidergrams for the Kikkertavak tholeiites (Figure 5) show a deepening of the Sr anomaly with increasing incompatible element concentration. The most primitive samples in the spidergram have no Sr anomaly. This pattern suggests that the Sr anomaly is entirely developed by plagioclase fractionation.

Figure 16 shows Fe_2O_3 percent against the measured Sr anomaly (Sr*) for the Kikkertavak and Harp dykes. In both swarms, the Sr anomaly is clearly highly sensitive to increases in Fe_2O_3 content. Apart from a few dyke-centre samples that plot with positive Sr anomalies, which are probably due to the accumulation of feldspar crystals, samples plotted with anomalies approaching zero ranged between 10 to 16 percent Fe_2O_3. The onset of plagioclase fractionation quickly drives the Sr anomaly to be deeply negative as Fe_2O_3 content increases.

Spidergrams for the Kikkertavak and Harp tholeiites (Figures 3 and 9) showed that most samples have a pronounced negative Nb anomaly. Similarly, Figure 17 shows that the most iron-poor tholeiites in both swarms are strongly depleted in Nb, with normalized Nb/La = 0.2. More iron-rich magmas showed higher normalized Nb/La ratios with Nb/La > 1 in samples from both swarms where Fe_2O_3 is > 18 percent.

The two Kikkertavak dyke samples with primordial mantle-normalized Nb/La>1 correspond to two data points that have much higher Nb/Zr ratios than the rest of the Kikkertavak tholeiitic sequence on Figure 21. High V (Figure 15) and TiO_2 (Figure 20) contents are also present in these samples, and therefore, these samples may represent cumulates containing large amounts of ilmenitic or titanomagnetitic material.

Similarly, the high-magnesian dykes classified as belonging to the Kikkertavak swarm show a large variation in CaO:MgO ratios (Figure 13) and may contain cumulate material, though their spidergrams show similar negative Sr and Nb anomalies to the Kikkertavak tholeiites (Figure 4).

The Harp dykes show a similar trend to the Kikkertavak tholeiitic dykes in Fe_2O_3 vs. V (Figure 15), Fe_2O_3 vs. normalized Nb/La (Figure 17) and Fe_2O_3 vs. TiO_2 (Figure 20), suggesting that the two dyke swarms were formed by comparable geochemical processes. The high-magnesian–high-iron dykes classified as belonging to the Harp swarm are those more enriched in TiO_2, V and Nb and also have distinctly higher Nb/Zr ratios than other Harp tholeiites (Figure 21). The described petrography of these rocks suggests that they contain cumulates of olivine and/or titaniferous

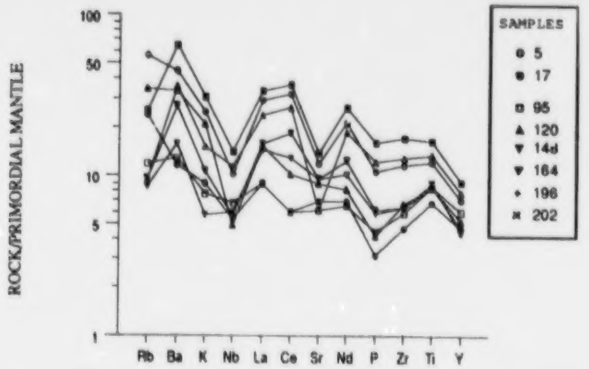

Figure 3. *Spidergram for Kikkertavak tholeiitic dykes. Note the Nb and Sr negative anomalies and the variable Rb/Ba ratio.*

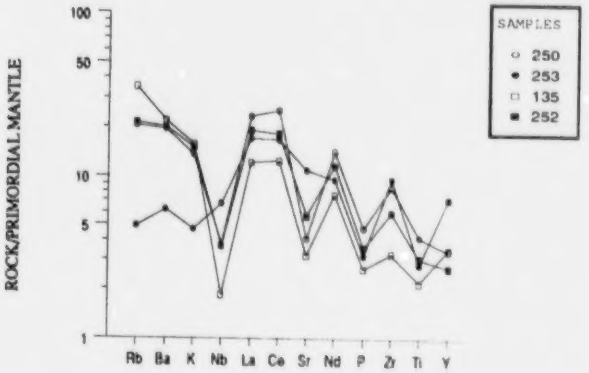

Figure 4. *Spidergram for high-magnesian dykes of suspected Kikkertavak age.*

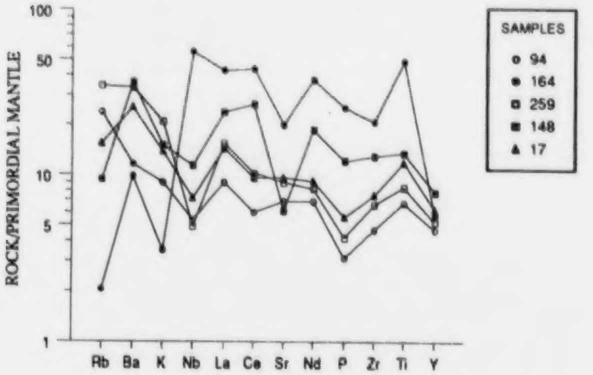

Figure 5. *Spidergram for selected Kikkertavak tholeiites, showing the development of the Sr anomaly in dykes with higher incompatible element abundances.*

phases, as the reaction rims on the olivine phenocrysts suggest non-equilibrium with the predominantly metal oxide groundmass.

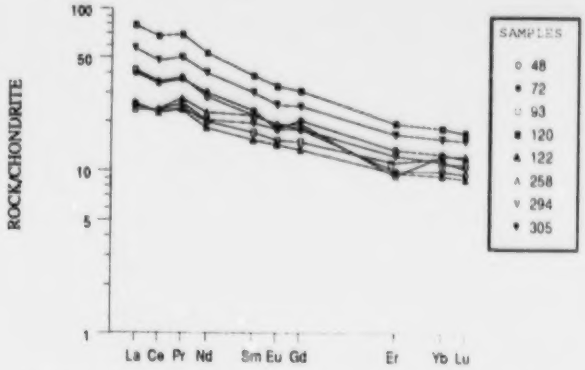

Figure 6. *Plot of rare earths for Kikkertavak tholeiites, showing slight HREE depletion.*

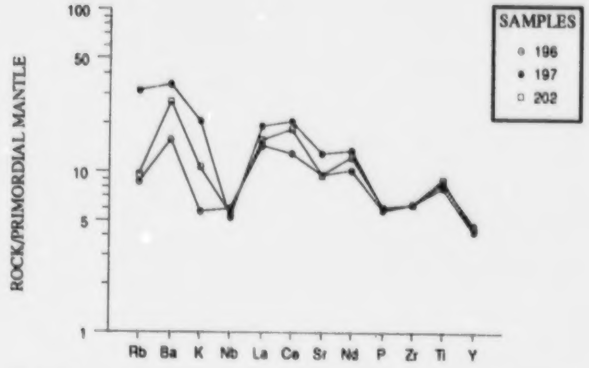

Figure 7. *Plot of three samples representing the margins (hollow symbols) and centre of a single Kikkertavak dyke. The depletion of Rb at the margins suggests that the wall rock has not contributed incompatible elements to the dyke margins.*

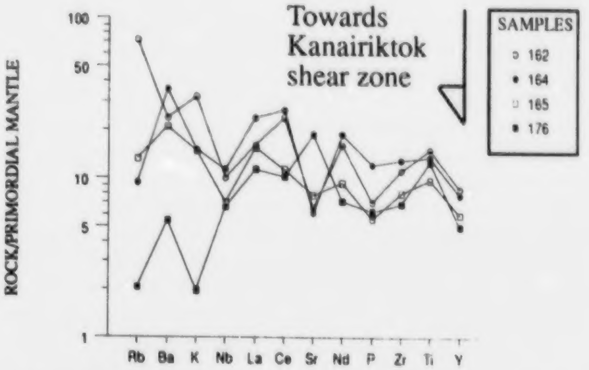

Figure 8. *Plot of samples in a single dyke in descending order toward the Kanairiktok shear zone, showing the progressive depletion in large-ion lithophile elements.*

Rare-earth patterns for the Kikkertavak tholeiitic suite show a consistent heavy rare-earth depletion, which probably signifies the presence of garnet in the source residue (Figure

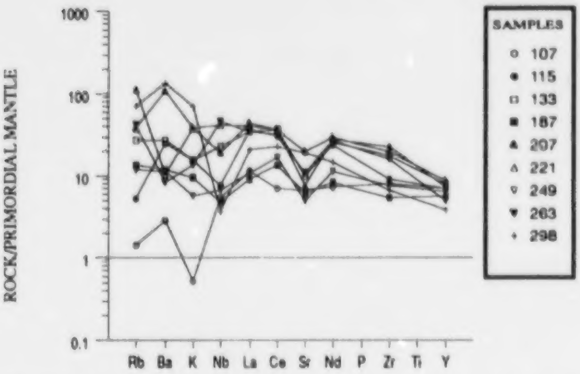

Figure 9. *Spidergram for Harp tholeiitic dykes. Note the similarity to Kikkertavak dykes in terms of negative Sr and Nb anomalies and highly variable LILE ratios and concentrations.*

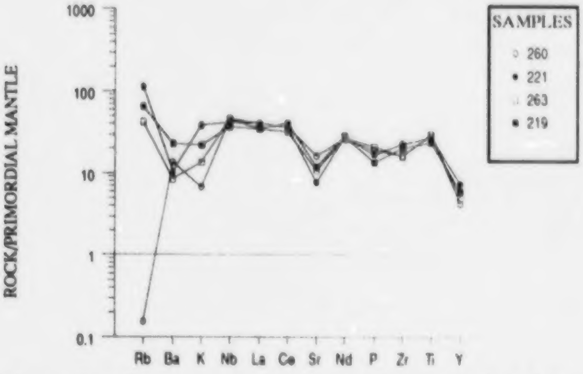

Figure 10. *Spidergram for high-iron–high-magnesium dykes of suspected Harp age.*

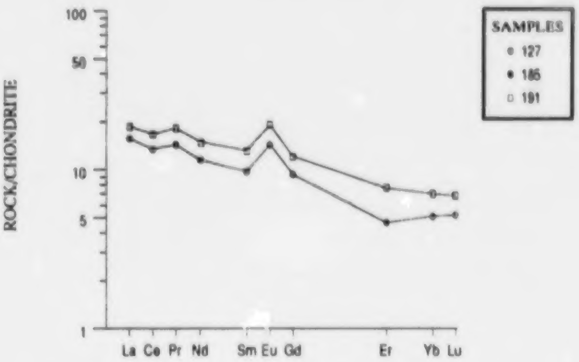

Figure 11. *Plot of rare earths for Harp dykes with positive Eu anomalies.*

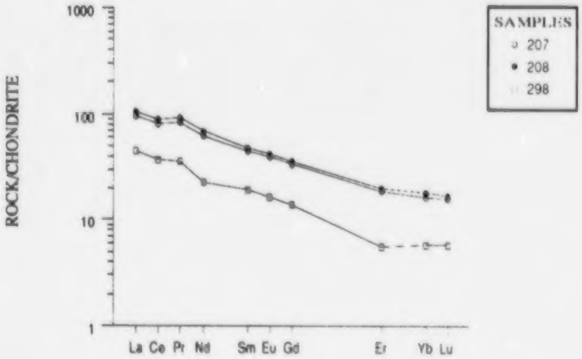

Figure 12. *Plot of rare earths for the Harp swarm showing higher La/Lu ratios compared to the first rare-earth group and no Eu anomaly.*

6), but no negative Eu anomaly (which would be consistent with plagioclase fractionation) suggesting that Eu was oxidized to its +3 valency state. In comparison, the Harp dykes show two distinct rare-earth patterns (Figures 11 and 12): one with a small positive Eu anomaly and a small degree of heavy rare-earth depletion, the second with no Eu anomaly but with much higher total abundances of rare earths and more pronounced heavy rare-earth depletion. Therefore, it appears that at least two different mantle sources supplied magma for the Harp swarm. The greater scatter in Harp data compared to Kikkertavak dykes in other Harker oxide variation diagrams (e.g., Figure 13) is in agreement with this conclusion.

Contamination and Alteration

The relationship between Rb and Ba in the spidergrams of the Kikkertavak and Harp dykes show great degrees of variation, which may reflect magma processes, wall-rock contamination or secondary alteration (Figure 18).

Crustal contamination is often invoked to explain the high concentrations of large-ion lithophile elements in continental flood basalts (e.g., Thompson, 1974, 1975). Assimilation and enrichment of large-ion lithophiles from the wall rocks may be expected to occur if magma was flowing turbulently; a condition thought to occur in basic dykes over 3 m in width (Huppert and Sparks, 1985), and therefore, in most Kikkertavak and Harp intrusions. Alternatively, dyke margins may become enriched in incompatible elements once dyke flow has stopped if the magma at the wall rock–dyke interface is still liquid ('Residence' contamination, Fratta and Shaw, 1974). However, there is no field evidence of wall-rock partial melting during emplacement of tholeiites of either the Kikkertavak or Harp dyke swarms: wall-rock irregularities can be matched on both sides of the dykes and dyke margins are always chilled. Dykes are always rectiplanar in outcrop and are associated with the process of emplacement by the dilation and linkage of *en echelon* crack arrays (Nicholson and Pollard, 1985). Therefore, processes of brittle failure dominated dyke intrusion and the exposed depth of intrusion is likely to have been upper crustal. Figure 7 shows a spidergram for margin-centre pairs of analyses for a Kikkertavak dyke. As Rb is more depleted at the dyke margins compared to the centre, this also suggests that contamination of the dyke by the wall rock at the exposed crustal level did

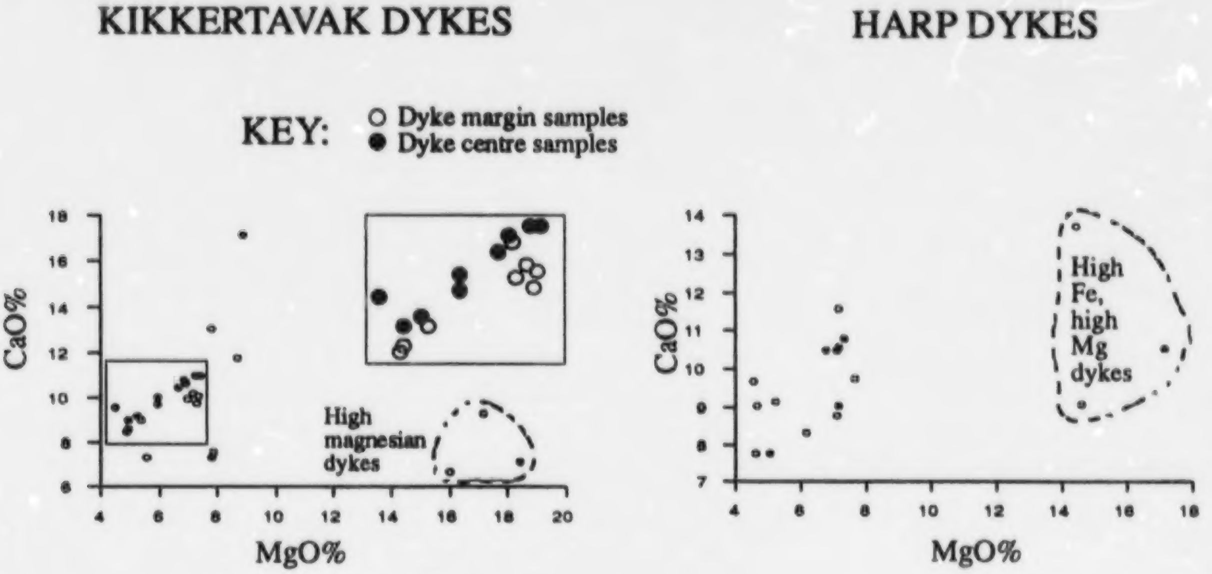

Figure 13. *Plots of CaO% versus MgO% for Kikkertavak and Harp dykes. Note the slightly more calcic nature of the dyke centres in the Kikkertavak swarm due to accumulation of plagioclase phenocrysts.*

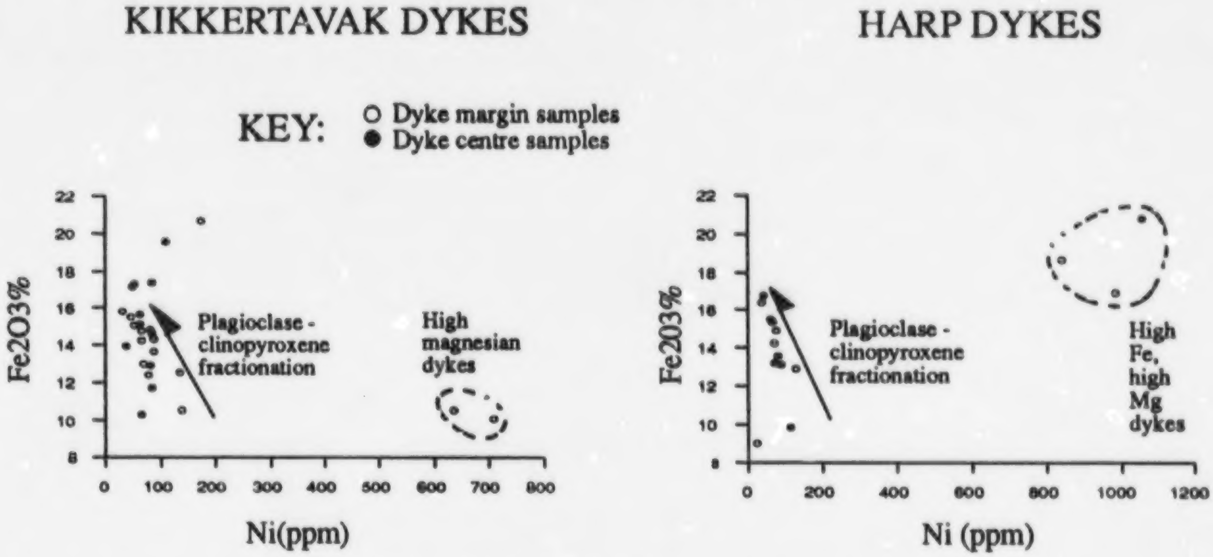

Figure 14. *Plot of Fe_2O_3% versus Ni (ppm).*

not occur, as the host Fiordian tonalite contains much greater abundances of Rb than the dyke.

There is no evidence of significant tilting in the Hopedale block after the injection of either swarm, and hence, progressively deeper crustal environments of intrusion where contamination is perhaps more likely, cannot be studied here. However, Archean terranes such as the Lewisian in northwest Scotland, intruded by the Scourie dyke suite, are exposed at mid-crustal levels. The Sourie dykes in this area still retain chilled margins and similarly do not show active assimilation of the more acidic wall rocks (Weaver and Tarney, 1981, 1983; Cadman *et al.*, 1990).

Another potential source of alteration is the Lower Proterozoic tectonism associated with the Kanairiktok shear zone: Kikkertavak dykes commonly show high degrees of metasomatic alteration within 10 km of the Makkovik Province–Hopedale block boundary, suggesting they may have been used as channelways by syn-tectonic migrating

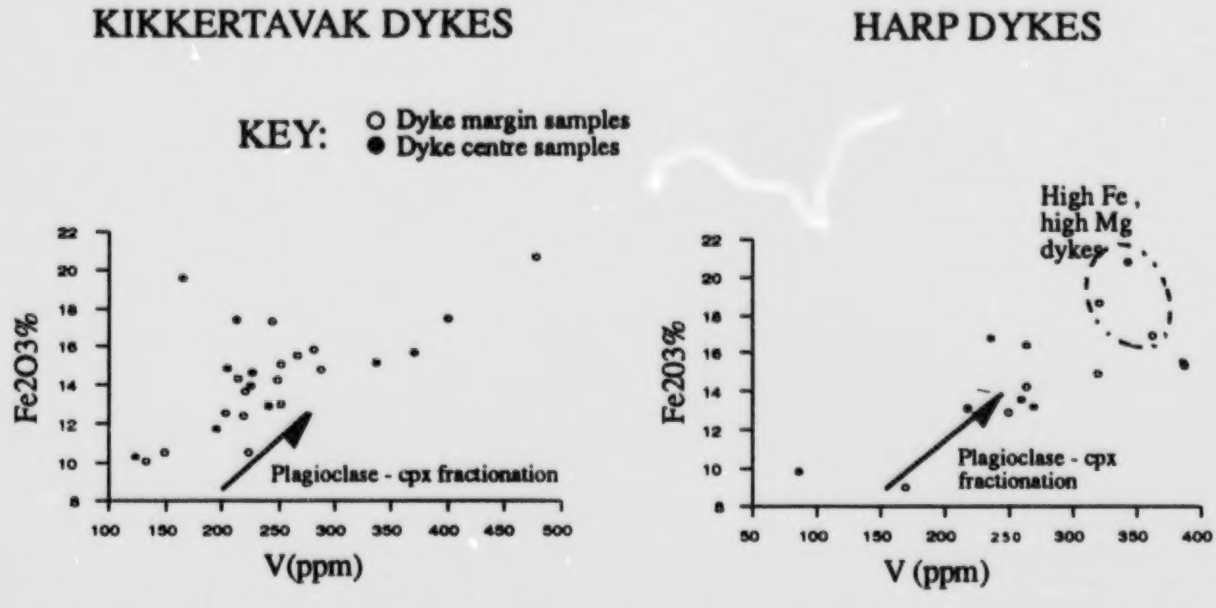

Figure 15. *Plot of Fe_2O_3% versus V (ppm).*

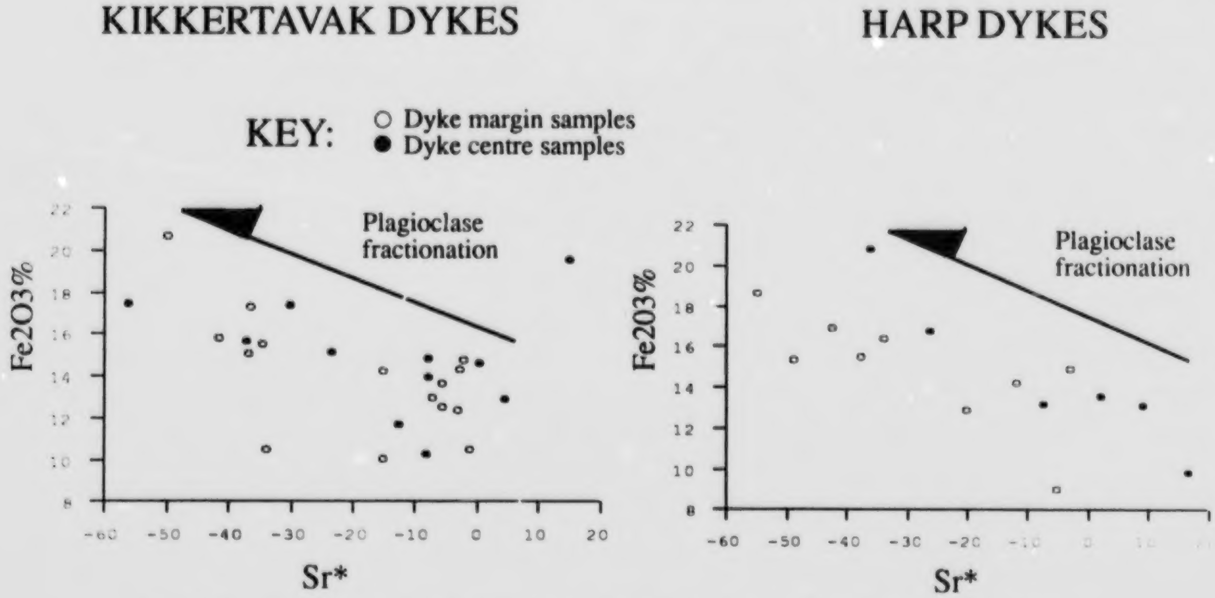

Figure 16. *Plots showing the development of Sr anomaly (Sr*) with increase in Fe_2O_3 content.*

fluids. The sheared dyke margins were often at high angles to the northeast-southwest orientation of the Kanairiktok shear zone and the presence of such fluids is more likely to be the dominant factor in initializing marginal shears rather than the prevailing orientation of shear stresses in the southern Hopedale block.

Figure 8 shows spidergrams for samples taken within 5 km of the Kanairiktok Bay shear zone. Samples taken closer to the shear zone show a progressive depletion in Rb and to a lesser extent, Ba.

This depletion in Rb in the Kikkertavak dykes relative to other large-ion lithophile elements approaching the shear zone can be seen clearly in Figure 18. The Rb anomaly (Rb*) is calculated relative to Ba and K. As the shear zone is approached, an initially positive Rb* begins to fall and becomes negative. Dyke-margin samples show higher levels

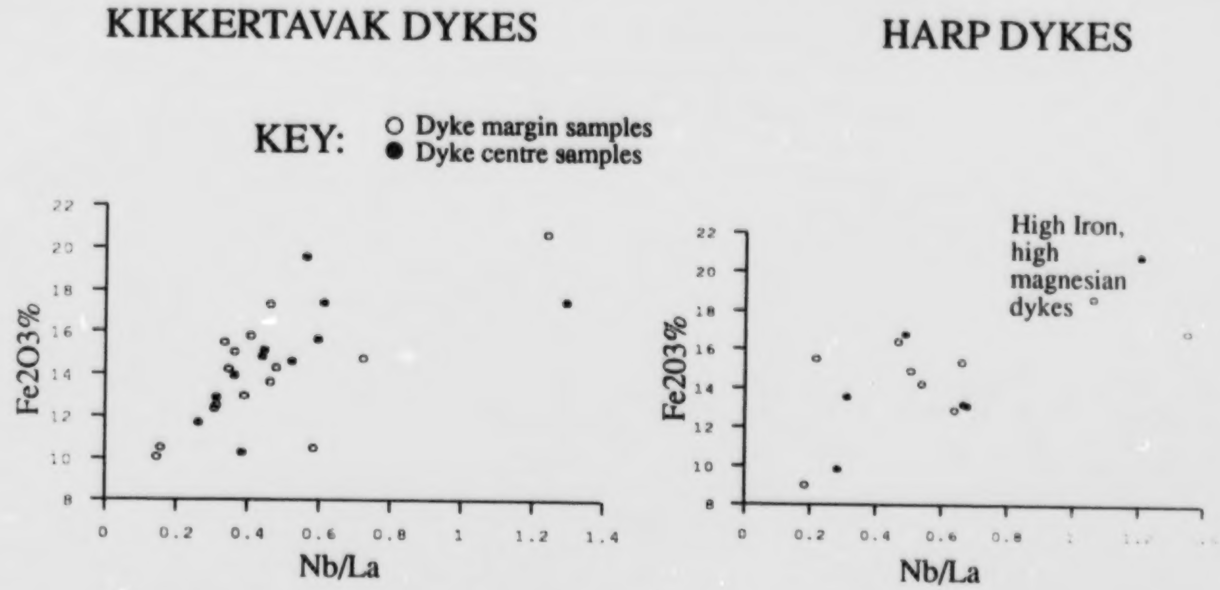

Figure 17. *Plots showing increase in Nb/La ratio (after normalization of both elements against primordial mantle abundances) with increasing* Fe_2O_3 *content.*

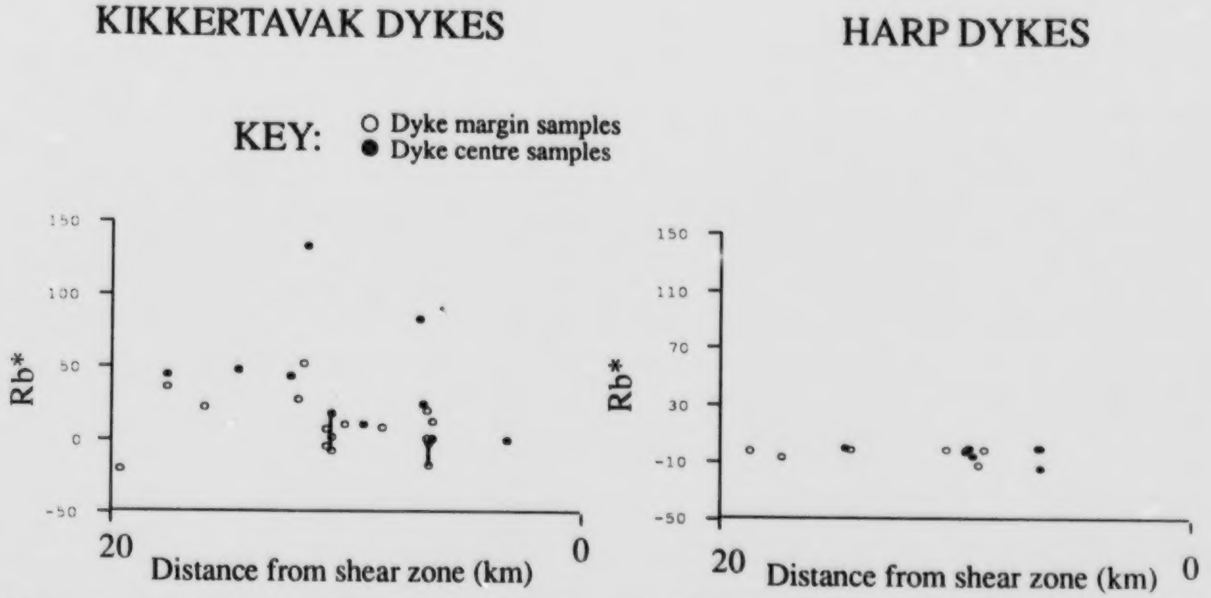

Figure 18. *Plots showing the differing behaviour of the Rb anomaly (Rb*) for Kikkertavak and Harp dykes approaching the Kanairiktok shear zone. Tie lines denote dyke-margin-centre sample pairs taken at same locality.*

of depletion than associated centres, which is in agreement with the observed tendency toward greater alteration.

Rb* becomes strongly positive at greater distances from the shear zone but remains highly variable. This confirms that the Kikkertavak dykes were affected by another alteration event unrelated to the Kanairiktok shear zone, as suggested by the pervasive low-grade alteration seen in the Kikkertavak dykes throughout the Hopedale block (Cadman, *this volume;* Ermanovics, 1979). Ermanovics (*in press*) states that this low-grade alteration is also seen in the Fiordian gneisses and is partially due to deuteric alteration in the dykes and might also be partially due to metamorphism and consequent dewatering of the Moran Lake Group, which may once have overlain much of the Hopedale block.

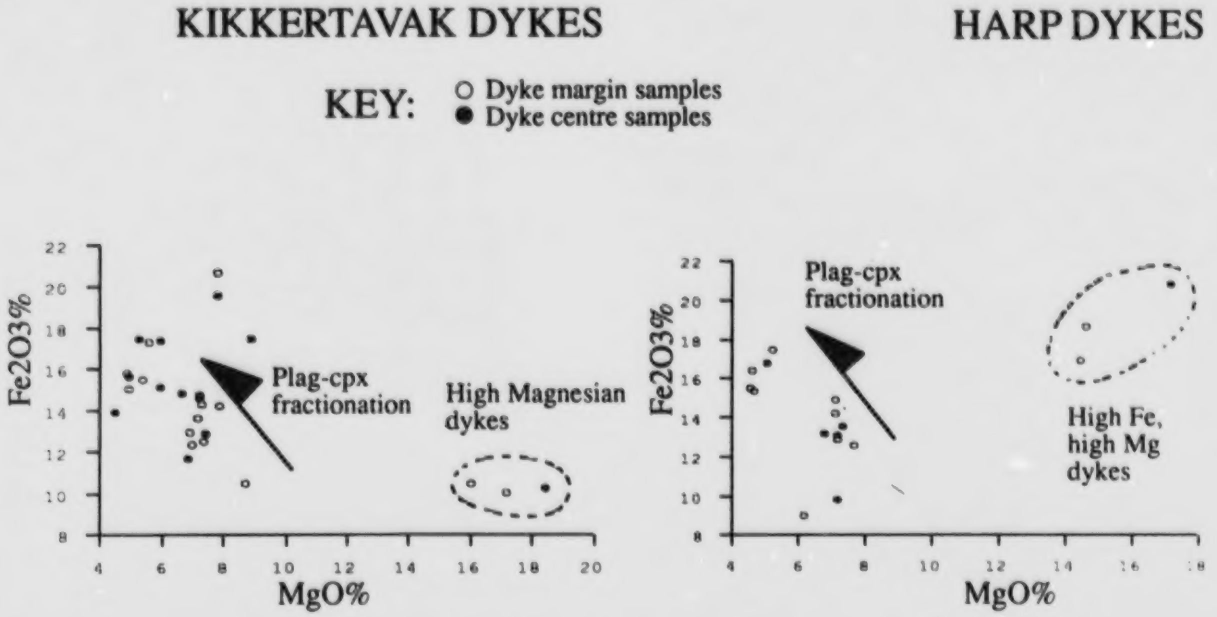

Figure 19. *The plot of Fe_2O_3% versus MgO% shows the general increase in Fe_2O_3 content with decreasing MgO as plagioclase and clinpyroxene are crystallized.*

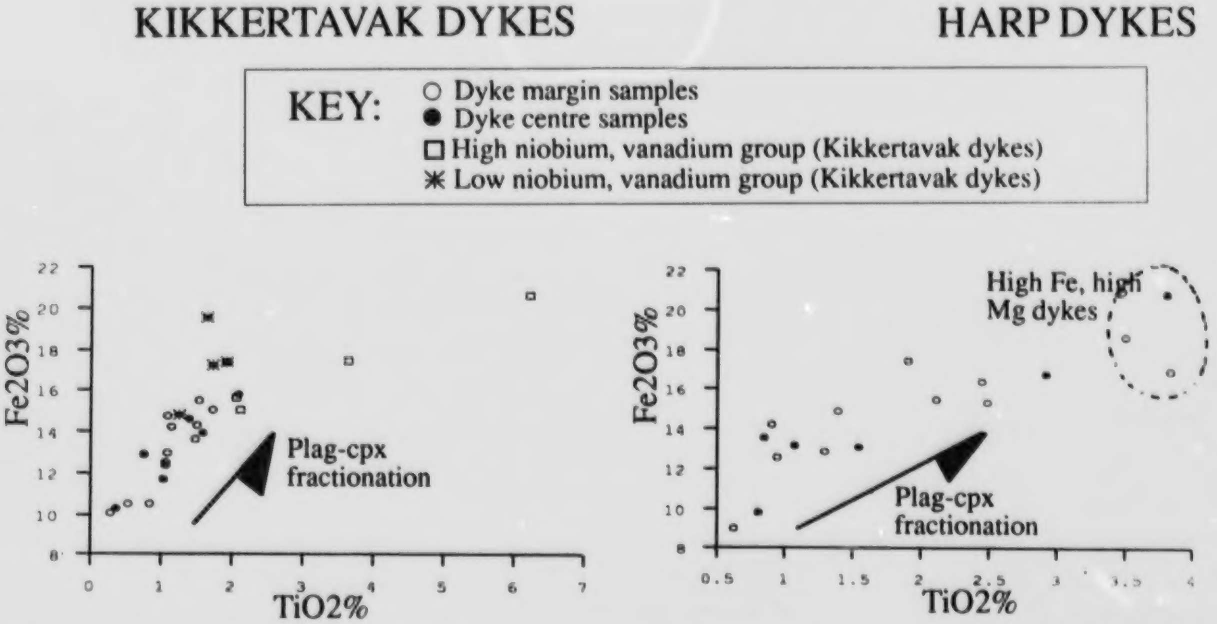

Figure 20. *Plots showing correlation in Fe_2O_3 and TiO_2 contents. In both swarms, the samples with high TiO_2 (Ti>3%) may not represent primary liquids.*

In comparison, the Harp dykes show a flat Rb* trend approaching the shear zone; the Rb anomaly is weakly negative and shows little variation, which is in concordance with the low alteration state of the Harp dykes.

THE KIKKERTAVAK AND HARP SWARMS: A COMPARISON OF MAGMATISM

The complex magma evolution patterns outlined above for both swarms, especially the Kikkertavak dykes, may be

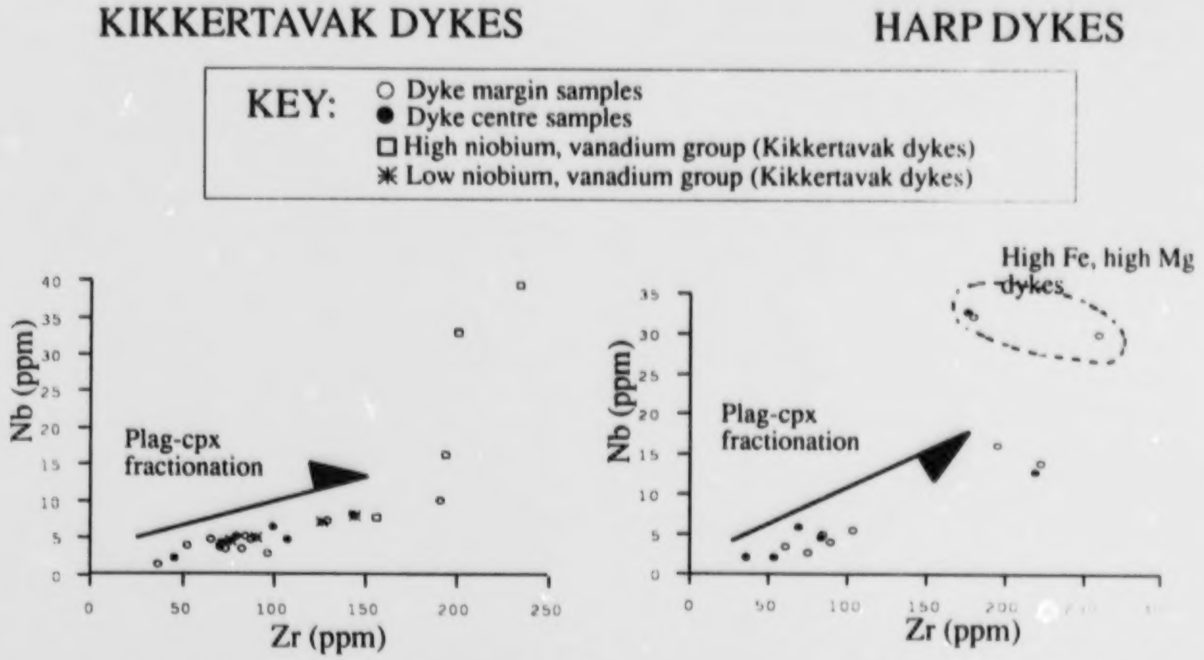

Figure 21. *These diagrams show most clearly of all that high Nb- and V-bearing samples currently attributed to both swarms do not lie on the tholeiitic fractionation trend and may represent cumulates or magmas derived from very different sources.*

due to initial mantle source heterogeneties, magma-chamber processes or a combination of the two.

Magma chambers are often invoked to explain significant degrees of fractionation and mixing by allowing comparitively long magma-storage times before dyke injection (e.g., Huppert and Sparks, 1985; Defant and Nielsen, 1989). Cox (1980) argues that the typically low Ni content of tholeiitic continental flood basalts and the good correlation between CaO and MgO suggest low pressure fractionation of clinopyroxene and plagioclase. However, Thomson (1974) showed that plagioclase–clinopyroxene crystallization was possible at Moho depths, and shallow-level or mid-crustal magma chambers are very rare considering the vast regions of flood basalts, or their root dyke swarms, that are exposed. Those that are, for example, the Muskox intrusion, often show a range of compositions that are not mirrored in the slightly later dykes (e.g., Mackenzie swarm; LeCheminant and Heaman, 1989) that crosscut them. The linear pattern of Proterozoic dyke injection is also very different from the radial or concentric patterns associated with the stress systems of magmatic centres, such as the radial swarm seen at Spanish Peaks, Colorado (Ode, 1957). The Harp dykes, for example, do not radiate outward from the Harp Lake gabbro–anorthosite complex, which they crosscut (Meyers and Emslie, 1977).

If magma chambers situated within the upper crust are not thought to exist in relation to either dyke swarm, then shallow-level processes must take place wholly within the evolving dyke system. The presence of gabbroic cumulate layers developed parallel to the dyke margins in some Kikkertavak intrusions supports a degree of shallow-level fractionation within individual dykes, though generally, in aphyric intrusions of either the Kikkertavak or Harp swarm, dyke centres are not significantly compositionally different from dyke margins. This suggests that active fractionation within the dyke conduit is small compared to the total amount of fractionation that has occurred in the system over time.

The presence of coarse, layered plagioclase–clinopyroxene cognate xenoliths and large gabbroic xenoliths (> 1 m) within Kikkertavak diabases (Cadman, *this volume*) suggests that magma-cooling rates decreased with depth and magma flow stagnated for long enough periods to allow gravity settling of material to take place. Magmatism during the intrusion of the Kikkertavak dykes seems to have consisted of cycles of high magma-flow rates punctuated by more quiescent periods. The partially resorbed cores, surrounded by euhedral overgrowths, seen in the plagioclase feldspars in many Kikkertavak dykes suggest that input of new magma pulses has driven evolving magmas back up the fractionation path. The incorporation of large cognate xenoliths, cumulate material and the scouring textures observed in one Kikkertavak dyke (Cadman, 1989, *this volume*) suggest that dyke paths were rejuvenated by the injection of high-energy magma flows that were capable of entraining solidified and fractionating material. Hence, processes that allow the cyclic build up and release of pressure, such as the emptying and refilling of a small magma chamber, have operated during dyke injection.

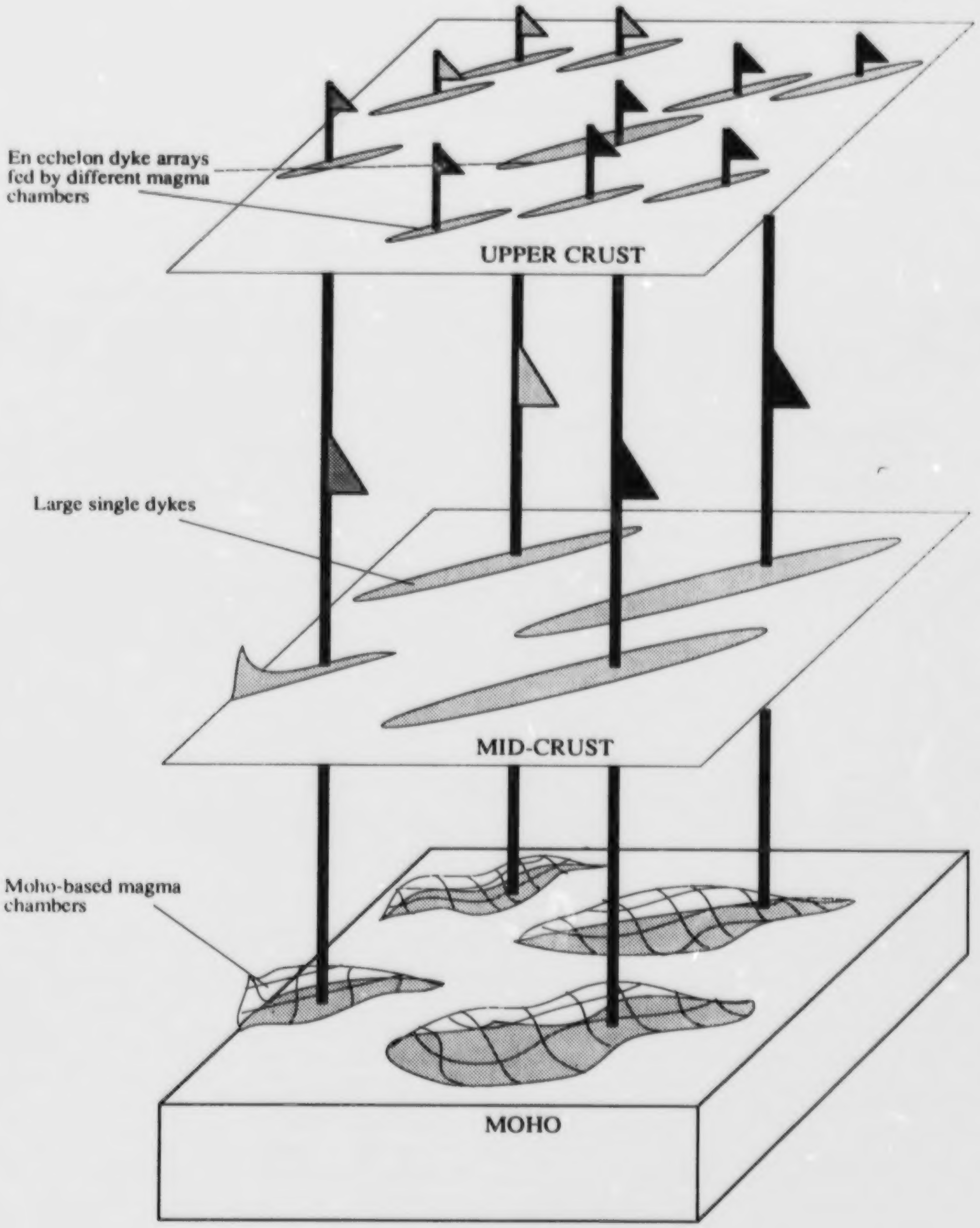
En echelon dyke arrays
fed by different magma
chambers
UPPER CRUST
Large single dykes
MID-CRUST
Moho-based magma
chambers
MOHO

Figure 22. *Diagram showing the relationship between dyking and discrete magma chambers.*

Bruce and Huppert (1989) show that the hotter initial temperatures of wall rock at mid- or lower-crustal depth would allow cooling rates in dykes to be many orders of magnitude slower than at upper-crustal conditions. An increase of dyke width at depth would allow even slower cooling rates. Consequently, rather than Moho-based magma chambers being single 'blisters' supplying magma for a whole dyke swarm, magma chambers could in fact be dyke-like bodies of linear or ellipsoid form. Each such magma chamber might feed one, or a small number of intrusions, which it directly underlies, in a linear array (Figure 22). Hence, each linear array of dykes would show little along-length variation but considerable variation between arrays of dykes across the width of the swarm would be possible.

The petrological differences seen between adjacent parallel basaltic and komatiitic intrusions in the Forte Frances swarm, Canada (Halls, 1986) support this argument. Similarly, the megacrystic texture observed in the Kikkertavak dykes is found sporadically within a narrow linear array of intrusions parallel to the strike of the swarm and only at one locality outside of this array.

In contrast, the Harp dyke swarm shows much less textural variation and may represent more stable magmatic injection into the crust, with dykes consisting of single-phase intrusions with no evidence of magma flow-rate fluctuations during emplacement. (The olivine crystals are, for example, out of equilibrium with the oxide-dominated groundmass judging from the alteration of their rims.) The more regular northeasterly trend of the Harp dykes for both diabases and gabbros suggests that the regional stress in the crust during this time had a significant northwest-southeast tensional component that allowed easy access of the magma into the crust. However, during injection of the Kikkertavak dykes sigma 3 crustal stresses were perhaps less consistent, resulting in a greater spread of dyke orientation for all but the widest dykes.

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REFERENCES

Bruce, P.M. and Huppert, H.E.
1989: Thermal control of basaltic fissure eruptions. Nature, Volume 342, pages 665-666.

Basaltic Volcanism Study Project
1981: Basaltic Volcanism on the Terrestrial Planets. Pergamon Press, New York, 1286 pages.

Cadman, A.C.
1989: The petrogenesis and emplacement of Proterozoic dyke swarms, Part 1: Initial findings and paths of further research. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 1-7.

This volume: The petrogenesis and emplacement of Proterozoic dyke swarms, Part 2: Geochemistry and Paleostress analysis.

Cadman, A.C., Tarney, J. and Park, R.G.
1990: Intrusion and crystallization features in Proterozoic dyke swarms. *In* Mafic Dykes and Emplacement Mechanisms. *Edited by* J. Parker, P. Rickwood and M. Tucker. Balkema, Rotterdam, pages 13-24.

Cox, K.G.
1980: A model for flood basalt vulcanism. Journal of Petrology, Volume 21, pages 629-650.

1983: The Karoo province of southern Africa: origin of trace element enrichment patterns. *In* Continental Basalts and Mantle Xenoliths. *Edited by* C.J. Hawksworth and M.J. Norry. Shiva Publications, Nantwich, pages 139-157.

Cox, K.G. and Hawkesworth, C.J.
1985: Geochemical stratigraphy of the Deccan Traps at Mahabaleshwar, western Ghats, India, with implications for open system magmatic processes. Journal of Petrology, Volume 26, pages 355-377.

Defant, M.J. and Nielsen, R.L.
1989: Interpretation of open system petrogenetic processes: phase equilibria constraints on magma evolution. Geochemica et Cosmochemica Acta, Volume 54, pages 87-102.

Ermanovics, I.F.
1979: Geology, Adlatok Bay–Florence Lake area, Labrador. Geological Survey of Canada, Open File 580.

1980: Geology of the Hopedale block of Nain Province, Labrador: Report 2. *In* Current Research, Part B. Geological Survey of Canada, Paper 80-1B, pages 11-15.

1981a: Geology, Ingrid Group map-area, Newfoundland (13N/5). Geological Survey of Canada, Open File 755.

1981b: Geology, Hunt River map-area, Labrador, Newfoundland (parts of 13N/7,9,10,15,16). Geological Survey of Canada, Open File 778.

1984: Geology of the Hopedale block, Labrador, Newfoundland (NTS 13N/1,2,3,5,6,7,8 and 13O/4,5). Geological Survey of Canada, Open File 1083, Map 2, 1:100,000 scale.

In press: Geology of the Hopedale block, southern Nain Province and the adjacent Proterozoic terranes, Labrador, Newfoundland. Geological Survey of Canada, Memoir 431, 200 pages.

Ermanovics, I.F. and Korstgaard, J.A.
1981: Geology of the Hopedale block and adjacent areas, Labrador: Report 3. *In* Current Research, Part A. Geological Survey of Canada, Paper 81-1A, pages 69-76.

Ermanovics, I. and Raudsepp, M.
1979: Geology of the Hopedale block of eastern Nain Province, Labrador: Report 1. *In* Current Research, Part B. Geological Survey of Canada, Paper 79-1B, pages 341-348.

Ermanovics, I., Korstgaard, J.A. and Bridgwater, D.
1982: Structural and lithological chronology of the Archean Hopedale block and the adjacent Proterozoic Makkovik subprovince, Labrador: Report 4. *In* Current Research, Part B. Geological Survey of Canada, Paper 82-1B, pages 153-165.

Fratta, M. and Shaw, D.M.
1974: 'Residence' contamination of K, Rb, Li and Ti in diabase dykes. Canadian Journal of Earth Sciences, Volume 11, pages 422-429.

Grant, N.K., Voner, F.R., Marzano, M.S., Hickman, M.H. and Ermanovics, I.F.
1983: A summary of Rb−Sr isotope studies in the Archean Hopedale block and the adjacent Proterozoic Makkovik Subprovince, Labrador: Report 5. *In* Current Research, Part B. Geological Survey of Canada, Paper 83-1B, pages 127-134.

Halls, H.C.
1986: Palaeomagnetism, structure and logitudinal correlation of Middle Precambrian dykes from northwestern Ontario and Minnesota. Canadian Journal of Earth Sciences, Volume 23, pages 142-157.

Huppert, H.E. and Sparks, R.S.J.
1985: The fluid dynamics of a basaltic magma chamber replenished by influx of hot dense ultrabasic magma. Contributions to Mineralogy and Petrology, Volume 75, pages 279-289.

Kranck, E.H.
1953: Bedrock geology of the seaboard of Labrador between Domino Run and Hopedale, Newfoundland. Geological Survey of Canada, Bulletin 26, pages 1-45.

LeCheminant, A.N. and Heaman, L.M.
1989: Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening. Earth and Planetary Science Letters, Volume 96, pages 38-48.

Loveridge, W.D., Ermanovics, I.F. and Sullivan, R.W.
1987: U−Pb ages on zircon from the Maggo Gneiss, the Kanairiktok Plutonic Suite and the Island Harbour Plutonic Suite, coast of Labrador, Newfoundland. *In* Radiogenic Age and Isotope Studies: Report 1. Geological Survey of Canada, Paper 87-2, pages 59-85.

Meyers, R.E. and Emslie, R.F.
1977: The Harp dykes and their relationship to the Helikian geological record in central Labrador. Canadian Journal of Earth Sciences, Volume 14, pages 2683-2696.

Nicholson, R. and Pollard, D.D.
1985: Dilation and linkage of en echelon cracks. Journal of Structural Geology, Volume 7, pages 583-590.

Ode, H.
1957: Mechanical analysis of the dyke pattern of the Spanish Peaks area, Colorado. Geological Survey of America Bulletin, Volume 58, pages 567-576.

Sutton, J.S., Marten, B.E., Clark, A.M.S. and Knight, I.
1972: Correlation of the Precambrian supracrustal rocks of coastal Labrador and southwestern Greenland. Nature Physical Science, Volume 238, pages 122-123.

Taylor, F.C.
1971: A revision of Precambrian structural provinces in northeastern Quebec and northern Labrador. Canadian Journal of Earth Sciences, Volume 8, pages 579-584.

Thompson, R.N.
1974: Primary basalts and magma genesis. 1: Skye, northwest Scotland. Contributions to Mineralogy and Petrology, Volume 45, pages 317-341.

1975: Primary basalts and magma genesis. 2: Snake River Plain, Idaho, U.S.A. Contributions to Mineralogy and Petrology, Volume 52, pages 213-232.

Weaver, B.L. and Tarney, J.
1981: The Scourie dyke suite: petrogenesis and geochemical nature of the Proterozoic sub-continental mantle. Contributions to Mineralogy and Petrology, Volume 78, pages 175-188.

1983: Chemistry of the sub-continental mantle: inferences from Archaean and Proterozoic dykes and continental flood basalts. *In* Continental Basalts and Mantle Xenoliths. *Edited by* C.J. Hawkesworth and M.J. Norry. Shiva Publications, Nantwich, pages 209-229.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 205-215

PILLOW LAVAS IN THE DEAD ISLANDS AREA, GRENVILLE PROVINCE, SOUTHEAST LABRADOR

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Labrador Mapping Section

ABSTRACT

Pillow lavas have been recognized in dominantly amphibolite-facies mafic rocks, in the Dead Islands area, southeast Labrador. This occurrence is the first unequivocal example of pillow lavas in pre-Labradorian supracrustal rocks in the eastern Grenville Province. The pillow lavas occur with a dominantly pelitic supracrustal sequence that includes minor quartz- and calc-silicate-rich rocks, interpreted to be derived from metamorphosed banded chert and calcareous sedimentary protoliths, respectively.

Regionally, this sequence is part of the Paradise metasedimentary gneiss belt. The recognition of these pillow lavas strengthens the interpretation of more deformed and metamorphosed analogues elsewhere in the same metasedimentary belt as probably having a similar origin. The whole-rock geochemical compositions indicate that the volcanic rocks were not generated in an island-arc setting. Coupled with the sedimentary association, they might be interpreted as having formed in an intra-oceanic environment in which the magmatism had oceanic island affinities (either major ocean or back-arc), or in a passive margin or intra-continental rift. Analogies can be drawn in terms of sedimentary and magmatic character with the Aldridge Formation of southern British Columbia, which hosts the Sullivan SEDEX deposit, and with the environments of some Besshi-type deposits. The presence of abundant sulphide-rich gossans, in association with distal clastic sediments and banded chert, suggests a grassroots-exploration potential for sediment-hosted exhalative sulphide deposits in the Paradise metasedimentary gneiss belt and, by analogy, in other paragneiss successions in the Grenville Province of Labrador.

INTRODUCTION

The purpose of this paper is to report on an occurrence of unequivocal mafic pillow lavas in the Grenville Province in southeast Labrador. There are three reasons for doing this: (i) to provide indirect supporting evidence for the submarine, extrusive origin of other mafic rocks in pre-Labradorian supracrustal sequences in the area; (ii) to use the presence and geochemical characteristics of the mafic pillow lavas to infer the depositional and tectonic setting; and iii) to suggest the possibility of a hitherto unrecognized mineral-exploration potential for sediment-hosted massive sulphide deposits of either SEDEX (Morganti, 1988; Goodfellow *et al.*, 1990) or Besshi (Mitchell and Bell, 1973; Slack and Shanks, 1989) types in the Grenville Province of Labrador.

Supracrustal rocks predating Labradorian orogenesis are widespread in the eastern Grenville Province (defined here as that part of the Grenville Province shown in the inset to Figure 1). The most widespread pre-Labradorian supracrustal rock type is pelitic to semipelitic gneiss, which is locally interlayered with quartz-rich sediments (interpreted as quartzite and/or banded metachert), calcareous sediments, and banded mafic rocks. In sequences of quartzofeldspathic rocks that lack aluminosilicate or other minerals characteristic of a pelitic protolith, quartzite and calcareous metasediments are invaluable in confirming the sedimentary protolith of the overall sequence.

The use of mafic meta-igneous rocks to interpret the protolith of strongly deformed and metamorphosed sequences is more difficult however, as such rocks could be either extrusive or intrusive. If they are mafic intrusions, they clearly cannot be used to suggest whether a given package of quartzofeldspathic gneisses is orthogneiss or paragneiss. One criterion that is commonly interpreted as indicating a probable supracrustal origin for strongly deformed and metamorphosed rocks is compositional banding. Rocks that lack such banding (in the absence of more definitive evidence such as crosscutting contacts against an older compositional layering) are commonly interpreted as mafic dykes. Although this method of discrimination must suffice in the absence of better evidence, it is inherently unsatisfactory, as metamorphism and deformation may either obliterate or create compositional layering.

Therefore, the recognition of unequivocal mafic pillow lavas in the eastern Grenville Province is of considerable significance as it provides proof of a subaqueous, extrusive origin. Furthermore, preservation of pillows is evidence of comparatively moderate deformation and metamorphism,

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[1] Mineral Deposits Section

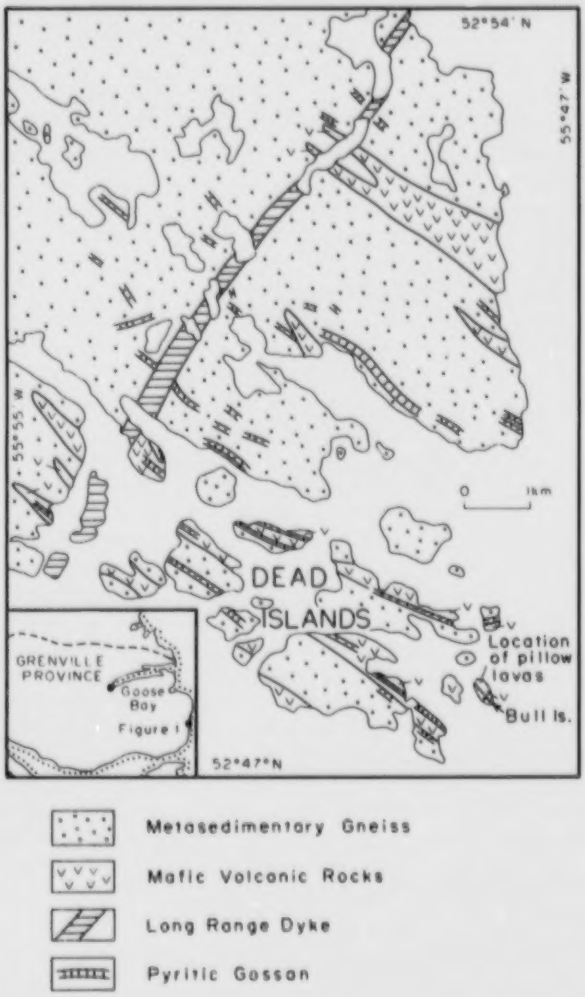

Figure 1. *Geology of the Dead Islands area, southeast Labrador. The location of the area within the eastern Grenville Province is shown in the inset. Location of pillow-lava locality on Bull Island is also shown.*

which provides an incentive to carry out geochemical studies in order to interpret the tectonic setting of volcanism. Because interpretations of predictive metallogeny are commonly closely tied to interpretations of tectonic environments (at least in the case of syngenetic deposit types), such interpretations may suggest exploration potential for specific deposit types.

GEOLOGICAL SETTING

The pillow-lava locality is on Bull Island at the southeastern end of the Dead Islands group. The distribution of rock types in the surrounding area is shown in Figure 1 (adapted from Gower *et al.*, 1988). Apart from mafic dykes and minor granitoid intrusions (neither of which are shown in Figure 1) and a northeast-trending Long Range dyke, the area is underlain entirely by supracrustal rocks. In the area shown in Figure 1, the pelitic gneisses are pink-, black-, grey- or buff-weathering, medium- to coarse-grained, quartz–K-feldspar–biotite–magnetite ± cordierite ± sillimanite ± garnet ± retrograde muscovite rocks. These gneisses are intimately associated with white-, grey- or creamy-weathering metasedimentary diatexites. Calc-silicate rocks and quartzite are interlayered with the pelitic rocks, although they are rarely extensive enough to be shown as separate units at the scale of mapping (1:100,000). Pyritic gossan, which may be metamorphosed banded chert, is a particularly characteristic rock type in the Dead Islands area.

Mafic rocks, comprising green to black, homogeneous to well-banded, fine- to medium-grained amphibolites, are interlayered with the metasedimentary rocks. The characteristic mineral assemblage in the amphibolite is hornblende and plagioclase, and they commonly contain lenses or pods of calc-silicate minerals, such as grossularite and diopside. Gower *et al.* (1987) suggested that some of the amphibolite was derived from mafic pillow lavas and included a photograph of part of an outcrop showing an example of pillows. It was during a subsequent excursion that included re-examination of this outcrop, that the mafic pillow lavas described here were discovered.

Geological features of the Bull Island mafic pillow lava locality are illustrated on Plates 1 to 4. The outcrop is composed of both pillowed and unpillowed flows. In Plate 1, the irregular-surfaced area on the right and centre rear is composed of pillow lava, in contrast to the front left area, which is composed of unpillowed mafic lava. The sequence has been intruded by a prominent mafic dyke. Details of the pillows are shown in Plates 2 and 3. Individual pillows are moderately flattened, generally less than 40 cm in diameter, and have thick margins and locally an internal radial structure which may have originally been defined by vesicles (Plate 3). Quartzofeldspathic mobilizate is locally present between the pillows. Thin layers of siliceous, laminated sediment are locally preserved between unpillowed flows (Plate 4).

Plate 1. *Overview of outcrop at the Bull Island pillow-lava locality. Pillow lavas are at the right and centre rear. Unpillowed flows are in the left foreground.*

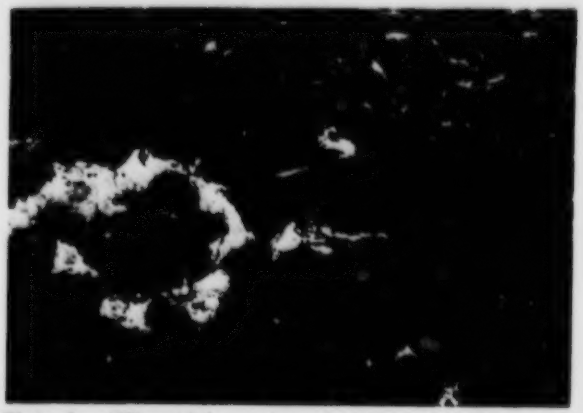

Plate 2. *Ellipsoidal, moderately flattened pillows with clearly defined pillow margins and white quartzofeldspathic leucosome material.*

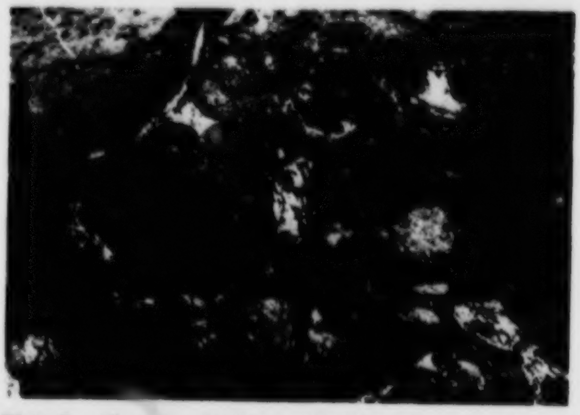

Plate 3. *Close-up of pillows with thick pillow margins and radial vesicles(?) in pillow interiors. White quartzofeldspathic leucosome between pillows. Felt-tipped marker in upper left for scale.*

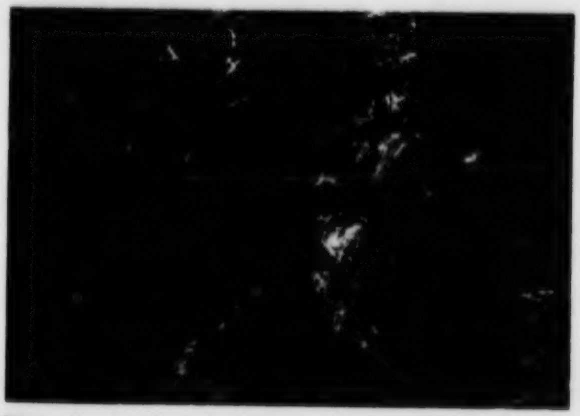

Plate 4. *Laminated siliceous clastic sediment between unpillowed flows, width of area shown in foreground is 3 m.*

GEOCHEMISTRY OF THE PILLOW LAVAS

ANALYTICAL METHODS

Major-element oxides and the trace elements Ba, Zr and Cr were determined by lithium metaborate fusion followed by analysis by inductively coupled plasma–optical emission spectrophotometry (ICP-OES), and the trace elements Ni, V, Rb, Sr, Cu, Pb and Zn, by total, multi-acid digestion and ICP-OES determination, all in the Newfoundland Department of Mines and Energy laboratory. The rare-earth elements (REE), the trace elements Sc, Th, Ta, Nb and Y were analyzed at Memorial University of Newfoundland using inductively coupled plasma–mass spectrometry (ICP-MS), according to analytical techniques described by Jenner *et al.* (1990). Precision for Th and the REE (excluding Eu and Lu) is better than 3 percent, for Eu and Lu it is 4 percent, and for Nb 7 percent.

Results

Whole-rock analyses of 3 samples taken from the Bull Island pillow-lava locality are presented in Table 1. Silica contents (44.05 to 45.20 percent) are in the basalt range and the rocks contain variable but high concentrations of TiO_2 (1.58 to 3.16 percent) and other incompatible elements. The Nb/Y ratios are approximately 0.8, and the rocks are mildly alkalic basalts according to the Winchester and Floyd (1977) discrimination diagram (Figure 2), consistent with silica concentrations. Other high-field-strength relationships also indicate a mildly alkalic or transitional tholeiitic composition for these rocks as displayed, for example, on the Nb–Zr–Y diagram (Figure 3). In this diagram, the samples plot in the field of overlap between within-plate tholeiitic and alkalic basalts.

The Mg# (defined as the molecular ratio [100*MgO]/[MgO+FeO]) ranges from 65 to 40, indicating that the samples have experienced variable low pressure fractional crystallization and that, collectively, they represent a considerable range of fractionation.There are considerable variations in the absolute concentrations of many compatible (e.g., Ni, Cr) and incompatible (e.g., Ti, Zr) elements, but incompatible element ratios for all three samples are constant and typical of within-plate tholeiitic and alkalic basalts (e.g., Zr/Y–Zr, Figure 4; Ti-Zr-Y, Figure 5), suggesting that they all represent the same source area, and probably the same parent magma.

Extended REE patterns (Figure 6) show a pronounced light rare-earth-element (LREE) enrichment and decrease smoothly to the heavy rare-earth elements (HREE). Thorium is negative with respect to La on a normalized basis and there is no negative Nb or Ta anomaly; both are important considerations in interpretations of tectonic setting (see below). There is no evidence that the magma sources might have been influenced by a subducting slab, nor the magmas contaminated by continental crust during ascent (cf. Wood *et al.*, 1979; Sun, 1980; Swinden *et al.*, 1990).

Table 1. Analyses of pillow lavas from the Dead Islands locality

Sample	2141074	2141075	2141076
SiO_2	45.20	44.35	44.05
TiO_2	3.16	1.58	1.99
Al_2O_3	14.21	9.93	11.63
Fe_2O_3	17.30	11.28	12.32
MnO	0.23	0.16	0.17
MgO	5.17	9.44	8.46
CaO	9.83	19.48	16.42
Na_2O	2.77	1.42	2.14
K_2O	0.69	0.23	0.16
P_2O_5	0.37	0.18	0.23
Total	98.93	98.05	97.57
Cr	17	1441	883
Ni	45	548	383
Sc	32	27	30
V	403	238	287
Cu	224	45	30
Pb	3	2	2
Zn	153	83	95
Rb	20	4	3
Ba	306	80	54
Sr	407	357	411
Ta		0.68	0.93
Nb	27	12	15
Zr	248	105	140
Y	33	15	20
Th		1.04	1.71
La	22.7	9.9	14.43
Ce	54.3	24.6	34.58
Pr	7.4	3.5	4.71
Nd	32.4	14.8	20.09
Sm	7.6	3.7	4.75
Eu	2.3	1.2	1.54
Gd	8.1	4.0	5.38
Tb	1.2	0.6	0.73
Dy	6.8	3.3	4.29
Ho	1.3	0.6	0.8
Er	3.4	1.7	2.2
Ta	0.5	0.2	0.28
Yb	2.9	1.4	1.78
Lu	0.4	0.2	0.25
Mg#	40	65	60

The range of absolute concentrations of some elements is readily interpreted in terms of low pressure fractional crystallization of a single magma. Incompatible elements including Ti, V, Zr, Y and the REE all increase regularly with decreasing Mg# (used here as an indicator of fractionation) (Table 1) and the extended REE patterns are parallel with regularly increasing total abundances corresponding to decreasing Mg# (Figure 6). The Cr and Ni decrease regularly with Mg#, while Sc and the ratio Al_2O_3/TiO_2 decrease only slightly, suggesting that fractionating phases were dominantly olivine and Cr spinel. Minimal clinopyroxene and plagioclase crystallization may account for slight decreases in Sc and Al_2O_3/TiO_2 ratios with decreasing Mg#.

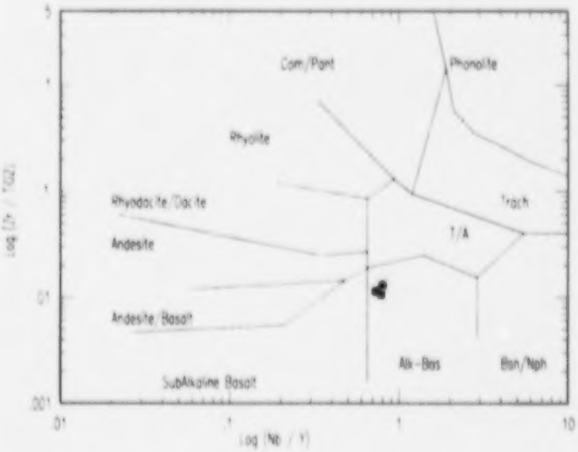

Figure 2. *Classification of the Dead Islands pillow lavas (solid squares) using immobile elements after Winchester and Floyd (1977). According to this diagram, they are mildly alkalic basalts.*

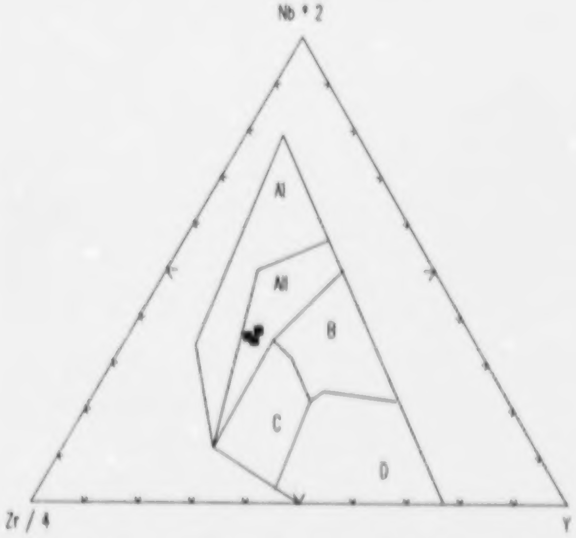

Figure 3. *Tectonic setting of the Dead Islands basalts (solid squares), using the trace-element diagram of Meschede (1986). Samples plot in field AII, the field of overlap between within-plate tholeiitic and alkalic basalts. Field AI is within-plate alkalic basalt, fields B, C, and D are MORB and volcanic-arc basalts. E-MORB and T-MORB (see text) would plot in field B.*

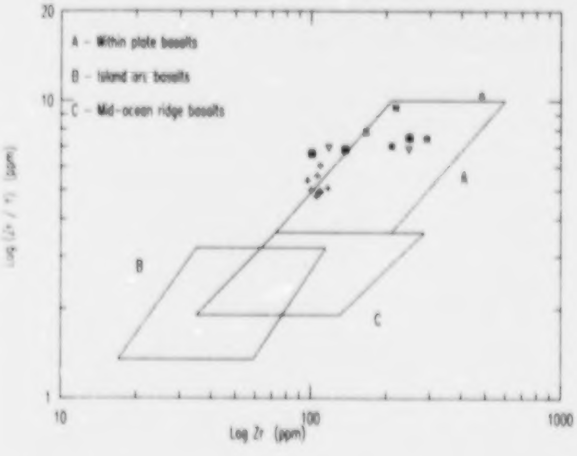

Figure 4. *Tectonic setting discrimination of the Dead Islands basalts (solid squares) according to the Zr–Zr/Y diagram of Pearce and Norry (1979). Shown for comparison are endmember Hawaiian alkalic basalts (upright triangles) and Hawaiian (Kilauean) tholeiites (inverted triangles) from the Basaltic Volcanism Study Project (1981) reference suite, Tibbett Hill formation basalts (asterisks) and alkalic sills from the Aldridge Formation (crosses). All plot in the field of within-plate basalts. See text for discussion.*

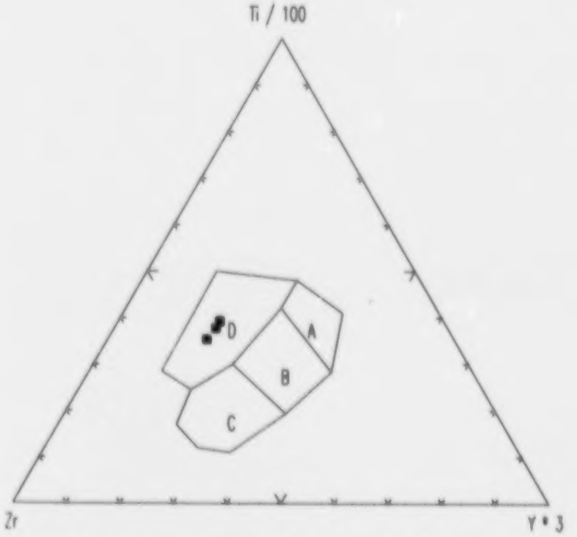

Figure 5. *Further illustration of the within-plate setting (Field D) of the Dead Island basalts (solid squares) according to the Pearce and Cann (1973) triangular diagram. Fields A, B, and C are MORB and volcanic-arc basalts.*

The dramatic increase in Ti, V and Fe with fractionation is characteristic of tholeiitic trends and suggests that neither hornblende nor iron–titanium oxides was present on the liquidus. The rocks are best interpreted as variably fractionated transitional tholeiites to mildly alkalic basalts, erupted in a within-plate tectonic setting.

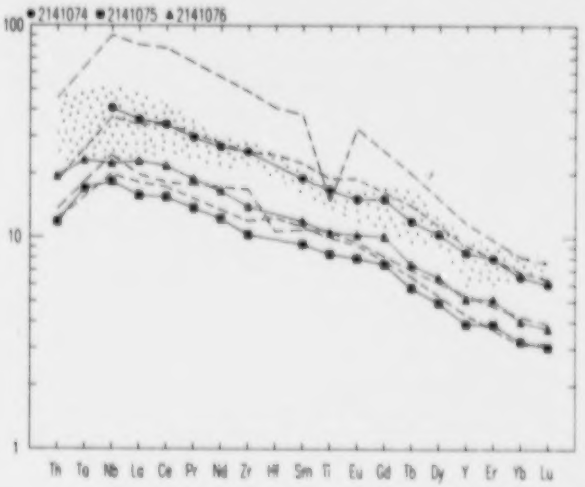

Figure 6. *Extended REE plot of the Dead Island basalts. The stippled field is the Tibbett Hill volcanics (passive margin rift sequence) from the data of Coish et al. (1985). Broken lines encompass the range of Kilauean tholeiites, broken lines with dots encompass the range of Hawaiian alkalic basalts in the Basaltic Volcanism Study Project (1981) reference suite.*

DISCUSSION

REGIONAL EXTRAPOLATIONS

The supracrustal rocks underlying the area of Figure 1 are part of the Paradise metasedimentary gneiss belt (Gower *et al.*, 1987), which extends without break to the northwest side of Sandwich Bay, a distance of about 175 km (Figure 7). Discontinuous zones of metasedimentary gneiss also occur farther northwest (between Sandwich Bay and Rigolet), but as some of these occur in different tectonic terranes it is uncertain whether they are regionally correlative with the Paradise metasedimentary gneiss belt. The age of the metasedimentary gneiss in this belt is not known precisely. Schärer and Gower (1988) reported a U–Pb zircon date of 1654^{+29}_{-26} Ma for a sillimanite-bearing metasedimentary gneiss at the southern end of Sandwich Bay, and suggested that the date was either the average age for detrital zircon in the metasediment or that it is related to Labradorian metamorphism. Indirect age constraints based on ages obtained from other units in the area imply that the sequence is almost certainly older than ca. 1675 Ma and unlikely to predate ca. 1750 Ma.

Mafic rocks, inferred to be of supracrustal origin have been reported from various places in the Paradise metasedimentary gneiss belt and its discontinuous extensions north of Sandwich Bay (Gower *et al.*, 1983, 1985, 1986). Gower *et al.* (1985) drew attention to an outcrop of fine-

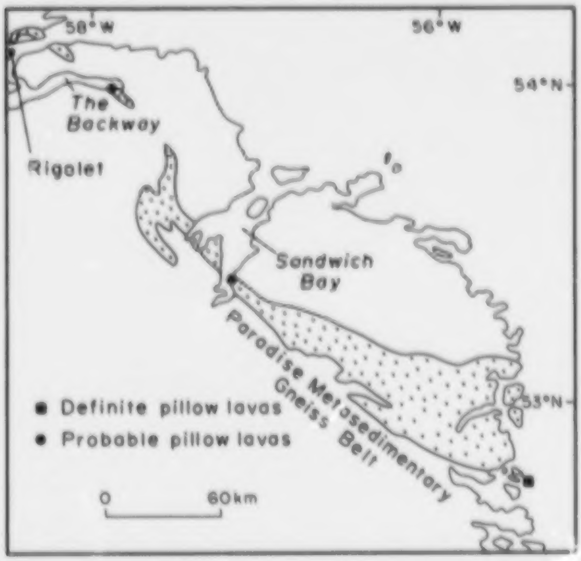

Figure 7. *Location of definite and probable pillow lavas in the Paradise metasedimentary gneiss belt and metasedimentary rocks farther northwest, southeast Labrador.*

grained amphibolite characterized by melanocratic seams and pods bearing calc-silicate minerals on the shoreline of Sandwich Bay, 4 km north of Paradise River, and compared it with similar rocks on the southeast shore of The Backway (Figure 7). As in the case of the Dead Islands pillow lavas, the calc-silicate pods were interpreted to represent calcareous interpillow material, and the melanocratic seams were suggested to be derived from pillow margins. With the recognition of unequivocal pillows at the Dead Islands locality, it now seems probable that these other occurrences are indeed derived from pillowed mafic volcanic rocks. Interpretation of the depositional and tectonic environment of the Paradise metasedimentary gneiss belt as a whole, should ideally consider all occurrences. It is worth reiterating the observation of Gower *et al.* (1985) that all three localities noted above are on the coast where exposure is very good. It is likely that similar mafic meta-igneous rocks (which are recessive-weathering) are more common inland than current maps would indicate.

Although rocks interpreted as pillowed mafic volcanics have not been found in other metasedimentary belts in eastern Labrador, minor occurrences of mafic rock, interlayered with other supracrustal rocks, have been described from other parts of Labrador. For example, Ryan *et al.* (1982) described finely layered amphibolite with narrow sulphide-rich zones along the southern edge of a thrust sheet south of the Red Wine River. This unit is probably correlative with the Beaver gneiss farther west, described by Emslie *et al.* (1978) as a metasedimentary gneiss having a relatively mafic appearance, but with local quartzofeldspathic interbeds and thin quartzite layers. In western Labrador, Nunn *et al.* (1984, 1986) and Connelly and Scowen (1987) have described banded, supracrustal mafic rocks as minor intercalations within metasedimentary gneiss. None of the occurrences outside eastern Labrador have been identified as having pillowform character.

Occurrences of mafic pillow lavas that may be pertinent to the late lower Proterozoic tectonic framework are found in the Stora Le-Marstrand Formation within the Sveconorwegian Orogenic Belt in coastal southwest Sweden (Ahäll, 1984; Hageskov, 1990), an area that is interpreted to have been relatively close to southern Labrador at that time (Gower and Owen, 1984). The pillowed mafic volcanic rocks identified by Ahäll (1984) were subsequently dated by Ahäll and Daly (1989) at 1758 ± 78 Ma (Nd–Sm, whole-rock), an age which is consistent with evidence for the age of the pillow lavas in southeast Labrador.

Depositional Setting

Aside from inferences of a pelitic sedimentary protolith (implying a distal clastic environment), little attempt has been made to characterize the depositional setting(s) of pre-Labradorian supracrustal rocks. Arima *et al.* (1986) noted that the metasedimentary gneiss in central Labrador is characterized by hematite as the dominant Fe-oxide. These authors suggested that the protolith was derived from two end-member components, one characterized by high SiO_2 and low REE, and the other by enhanced Al_2O_3, Fe_2O_3 and REE. They noted that the latter features are characteristic of weathering products of volcanic rocks.

The presence of pillow lavas in the Paradise metasedimentary belt shows that the depositional environment was at least locally subaqueous. The predominance of pelitic and cherty protoliths coupled with the absence of coarse clastic material suggests a relatively distal sedimentary environment.

Tectonic Setting

The tectonic setting of supracrustal rocks deposited prior to, or during the early stages of the Labradorian orogenic cycle, has not been established unequivocally. Two models have been favoured: (i) that the sediments were deposited as a Lower Proterozoic continental wedge that developed adjacent to the passive southern margin of proto-Laurentia; (ii) that the sediments were deposited in some form of island-arc environment, with which the subsequent (Labradorian) granitoid rocks were also associated (cf. Gower, 1990 for references). The latter model has gained some favour recently due to the absence of inherited zircons from early Lower Proterozoic or older crust in most samples of metasedimentary gneiss analyzed to date (Shärer and Gower, 1988; Currie and Loveridge, 1985; although see Thomas *et al.*, 1986 for the single exception).

The whole-rock compositions of the pillow lavas from southeast Labrador show that volcanic rocks, at this locality at least, probably did not form in an island-arc environment. The lack of positive Th and negative Ta and Nb with respect to La on the extended REE plots are diagnostic of magmatism that has not been influenced by a subducting slab (Wood *et al.*, 1979; Sun, 1980; Arculus and Powell, 1986; Swinden *et al.*, 1990). The geochemical data do not conclusively discriminate between the various non-arc environments that are permitted by the general geological relations, particularly as there are only three samples from a single outcrop. However, they do suggest a number of possibilities.

1) Passive margin rift

Tholeiitic to mildly alkalic mafic magmatism is characteristic of rifting of passive continental margins. An example of such rocks in the Appalachian Orogen is the Cambrian early rift volcanics of the northern Appalachians formed during rifting that eventually lead to formation of the Iapetus Ocean. The mafic magmatism ranges from tholeiitic to alkalic. Examples of mildly alkalic volcanic rocks from the Tibbett Hill Formation in Vermont (Coish *et al.*, 1985) are plotted on Figure 6 and show that volcanic rocks similar to those at the Dead Islands locality are represented in such an environment.

The possibility that these sequences represent a passive rift environment may be supported by recent geochronological data. Inherited zircons having ages of >1750 and 1735 Ma have been identified in a 1631 Ma hornblende granodiorite from the Mealy Mountains terrane (Schärer and Gower, 1988). This tends to support the idea that Pre-Labradorian crust was present on the southern flank of the Labrador Orogen, and was temporarily separated from proto-Laurentia prior to being accreted to the Laurentian margin during Laradorian orogenesis. Deposition of pre-Labradorian pelitic sediments and associated volcanic rocks in this rift basin would be consistent with such a tectonic scenario.

2) Epicontinental rift

Large epicontinental rift basins, formed through rifting of continental crust, are characteristic of the Proterozoic world-wide. Although generally sediment-dominated, these rifts are characterized by minor amounts of mafic magmatism, dominantly tholeiitic to alkalic in character. An example of such a sequence in the ancient record is the Purcell Supergroup of the Cordillera, in which the Aldridge Formation hosts the Sullivan massive sulphide deposit. Synsedimentary magmatism in this sequence is recorded by the Moyie diabase and gabbro sills, ranging from tholeiitic to mildly alkalic in character (Höy, 1989). Alkalic sills in the Aldridge Formation are geochemically similar to the Dead Island basalts (e.g., Figure 4).

Such a tectonic setting would also be consistent with the geochronological data noted above.

3) Within-plate oceanic magmatism (oceanic or back-arc basin)

Within-plate oceanic magmatism resulting, for example, from passage of an oceanic plate over a hotspot, commonly produces tholeiitic and alkalic basalt of oceanic island affinity (Basaltic Volcanism Study Project, 1981). This type of magmatism is characteristic of both major ocean and back-arc basins and may produce isolated seamounts or strings of seamounts (e.g., Hawaii). The Dead Islands basalts have clear affinities to this type of volcanism, as seen by comparison with both tholeiitic and alkalic eruptive rocks from Hawaii (Figure 6). The Dead Islands basalts plot in the field of overlap between Hawaiian tholeiitic and alkalic basalts.

4) Enriched spreading centre

Geochemically and isotopically enriched (or 'plume-type') volcanism characterizes many major oceanic and back-arc spreading centres (e.g., parts of the Mid-Atlantic Ridge, Schilling, 1973; Schilling *et al.*, 1983). The resulting rocks are commonly termed T-MORB or E-MORB (Transitional or Enriched Mid-Ocean-Ridge-Basalt), respectively, depending on the degree of enrichment. Although plume-type ridge volcanism typically produces rocks having geochemical characteristics similar to the Dead Islands pillow lavas, such rocks commonly plot in MORB fields on the Ti−Zr−Y diagram. Furthermore, the overwhelming dominance of sedimentary rocks is not supportive of such an environment and present evidence suggests this model is perhaps the least likely of those possible for the Paradise belt.

METALLOGENY

Known Mineralization

Sulphide occurrences are common and can be easily located in well-exposed coastal regions in the Paradise metasedimentary gneiss belt. In the Dead Islands and Occasional Harbour areas (cf. Gower *et al.*, 1987 and references therein), spectacular ocherous-weathering gossans are widespread and similar occurrences are known in the Sandwich Bay area, 150 km to the northwest (Gower *et al.*, 1985) as well as at The Backway and near Rigolet (Gower and Erdmer, 1984). Although gossans are uncommon in areas mostly covered by surficial deposits in the intervening area, the apparent continuity of the geological units between these areas provides a good reason to believe that sulphide occurrences are present throughout the whole belt. The main sulphide present is pyrite but minor chalcopyrite is also present locally. Douglas (1953) reported a grab sample containing 2.8 percent Cu from the Eagle River showing in the Sandwich Bay area and this area was also the focus of considerable geochemical and geophysical surveys by Brinex Limited (Sutton, 1965, 1966). Gower *et al.* (1987) reported Au assay values up to 37 ppb from grab samples in coastal outcrops.

Disseminated mineralization (magnetite, pyrite and pyrrhotite) is also associated with metasedimentary gneiss in interior parts of Labrador (Pyke, 1956).

Metallogenic Models

Syngenetic sulphide deposits occur widely in sediment-dominated environments where minor magmatism or rising geotherms related to rifting apparently provide the heat source to drive hydrothermal systems. Deposits of this type are variously called 'Besshi-type' or sedimentary exhalative ('SEDEX'), depending on the specific geological characteristics of the deposit, particularly the metal associations and the extent of volcanic activity (Sawkins, 1976; Slack and Shanks, 1989; Goodfellow *et al.*, 1990).

Besshi-type deposits (Mitchell and Bell, 1973; Sawkins, 1976; Slack and Shanks, 1989) are dominantly sediment-hosted, but are spatially and stratigraphically associated with significant volcanic activity. They commonly contain significant copper and locally zinc, silver, gold and/or cobalt. Most are Proterozoic or Paleozoic in age and the largest deposits of this type are in the 100- to 300-million tonnes range (e.g., Ducktown, Windy Craggy). The host sedimentary sequence is dominantly pelitic and the associated volcanic rocks range form MORB-like tholeiites to mildly alkalic basalt (Gair, 1988; Smith and Fox, 1989).

SEDEX deposits are dominantly Zn, Pb, barite deposits, with lesser Cu, Ag and Au. Most occur in Proterozoic and Paleozoic epicontinental rifts (e.g., Sullivan, Selwyn Basin) and are hosted by fine-grained deep-water clastic sedimentary rocks. Mafic magmatism is locally associated with these deposits. In the Selwyn Basin, as an example, it is dominantly alkalic basaltic. Syn-sedimentary sills in the Aldridge Formation stratigraphically associated with the Sullivan deposits range from tholeiitic to mildly alkalic (Höy, 1989). The alkalic sills are geochemically similar to the Dead Islands basalts (Figure 4).

The nature of the sedimentary succession in the Paradise metasedimentary gneiss belt and the geochemical character of the associated volcanic rocks would appear to be supportive of deposit models for either Besshi-type or giant SEDEX deposits. Interpretations of the sequence as either a passive margin rift or an epicontinental rift sequence allows for the formation of Besshi-type mineralization; an epicontinental rift interpretation supports SEDEX models. Interpretation of the sequence as a within-plate oceanic island or plume-type spreading centre would be less supportive of these metallogenic models. However, in the relatively unlikely event that we are dealing with a ridge crest, cupriferous massive sulphides might be expected to have formed at sites of hydrothermal discharge (e.g., the TAG and Snakepit fields, Mid-Atlantic Ridge; Rona *et al.*, 1986; Thompson *et al.*, 1988). Any of these would be worthy targets for regional grassroots exploration in a relatively unprospected environment such as the Paradise metasedimentary gneiss belt.

CONCLUSIONS

Amphibolite-facies mafic rocks from the Dead Islands area, southeast Labrador, are unequivocally identified as pillow lavas. This occurrence is the first to be reported from pre-Labradorian supracrustal rocks in the eastern Grenville Province. The pillow lavas occur within a dominantly pelitic supracrustal sequence that, regionally, is termed the Paradise metasedimentary gneiss belt. This occurrence lends support for a similar interpretation of more deformed and metamorphosed analogues that occur elsewhere in the same metasedimentary belt. The whole-rock compositions indicate that the pillow lavas are mildly alkalic basalts and indicate that these rocks were not erupted in an island-arc environment. The geochemical evidence, coupled with the geological relationships, suggests a number of alternatives for the tectonic environment including epicontinental rift, passive margin rift, within-plate oceanic islands, or plume-type spreading ridge. However, although the data are consistent with these environments, it would be unwise to extrapolate too far from such a small database. Further geological and geochemical work is needed to fully document the range of magmatism that occurred in this belt. Isotopic studies may be required to discriminate between intra-oceanic and continentally influenced environments.

Given the present state of knowledge, there would appear to be a good grassroots potential for exploration for sediment-hosted Besshi-type and SEDEX deposits in the Paradise belt.

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REFERENCES

Ahäll, K.I.
1984: Pillow lava in the Stora Le-Marstrand Formation, southwestern Sweden. Geologiska Forhandlingar, Volume 106, pages 105-107.

Ahäll, K.I. and Daly, J.S.
1989: Age, tectonic setting and provenance of Östfold-Marstrand belt supracrustals: westward crustal growth of the Baltic Shield at 1760 Ma. Precambrian Research, Volume 45, pages 45-61.

Arculus, R.J. and Powell, R.
1986: Source component mixing in the regions of arc magma generation. Journal of Geophysical Research, Volume 91, pages 5913-5926.

Arima, M., Kerrich, R. and Thomas, A.
1986: Sapphirine-bearing paragneiss from the northern Grenville Province in Labrador, Canada: protolith composition and metamorphic P-T conditions. Geology, Volume 14, pages 844-847.

Basaltic Volcanism Study Project
1981: Basaltic Volcanism on the Terrestrial Planets. Pergamon Press, New York, 1286 pages.

Coish, R.A., Fleming, F.S., Larsen, M., Poyner, R. and Seibert, J.
1985: Early rift history of the Proto-Atlantic Ocean: geochemical evidence from metavolcanic rocks in Vermont. American Journal of Science, Volume 285, pages 351-378.

Connelly, J.N. and Scowen, P.
1987: Geology of the Lac Caopacho–Lac Fleur-de-May area, southwestern Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 225-236.

Currie, K.L. and Loveridge, W.D.
1985: Geochronology of retrogressed granulites from Wilson Lake, Labrador. *In* Current Research, Part B. Geological Survey of Canada, Paper 85-1B, pages 191-197.

Douglas, G.V.
1953: Notes on localities visited on the Labrador coast in 1946 and 1947. Geological Survey of Canada, Paper 53-1, 67 pages.

Emslie, R.F., Hulbert, L.J., Brett, C.P. and Garson, D.G.
1978: Geology of the Red Wine Mountains, Labrador: the Ptarmigan Complex. *In* Current Research, Part A. Geological Survey of Canada, Paper 78-1A, pages 129-134.

Gair, J.E.
1988: Origin of unusual rocks at Ducktown, Tennessee, as indicated by rare-earth element geochemistry. Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists, Joint Annual Meeting, Programs with Abstracts, Volume 13, page A42.

Goodfellow, W.G., Lydon, J.W. and Turner, R.J.W.
1990: Current concepts on the origin of SEDEX deposits: Part I–geological and geochemical constraints. 8th International Association on the Genesis of Ore Deposits (IAGOD) Symposium, Ottawa, Canada, Program with Abstracts, page A189.

Gower, C.F.
1990: Mid-Proterozoic evolution of the eastern Grenville Province, Canada. Geologiska Föreningens i Stockholm Förhandlingar, Volume 112, pages 127-139.

Gower, C.F. and Erdmer, P.
1984: The mineral potential of paragneiss in the Grenville Province in eastern Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-1, pages 80-87.

Gower, C.F., Neuland, S., Newman, M. and Smyth. J.
1987: Geology of the Port Hope Simpson map region, Grenville Province, eastern Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 183-199.

1988: Port Hope Simpson map region. Newfoundland Department of Mines, Mineral Development Division, Map 88-88.

Gower C.F., Noel, N. and Gillespie, R.T.
1983: Groswater Bay 1:100,000 map sheet. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 83-44.

Gower, C.F., Noel, N. and van Nostrand, T.
1985: Geology of the Paradise River region, Grenville Province, Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 19-32.

Gower, C.F. and Owen, V.
1984: Pre-Grenvillian and Grenvillian lithotectonic regions in eastern Labrador–correlations with the Sveconorwegian Orogenic Belt in Sweden. Canadian Journal of Earth Sciences, Volume 21, pages 678-693.

Gower, C.F., van Nostrand, T., McRoberts, G., Crisby, L. and Prevec, S.
1986: Geology of the Sand Hill River–Batteau map region, Grenville Province, eastern Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 86-1, pages 101-111.

Hageskov, B.
1990: On the geology of the Koster archipelago. Field guide, Sveconorwegian Friends Excursion, 1990, 23 pages.

Höy, T.
1989: The age, chemistry and tectonic setting of the Middle Proterozoic Moyie sills, Purcell Supergroup, southeastern British Columbia. Canadian Journal of Earth Sciences, Volume 26, pages 2305-2317.

Jenner, G.A., Longerich, H.P., Jackson, S.E. and Fryer, B.J.
1990: ICP-MS–a powerful tool for high precision trace-element analysis in earth sciences: evidence from analysis of selected USGS reference samples. Chemical Geology, Volume 83, pages. 133-148.

Meschede, M.
1986: A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb–Zr–Y diagram. Chemical Geology, Volume 56, pages 207-218.

Mitchell, A.H.G. and Bell, J.D.
1973: Island-arc evolution and related mineral deposits. Journal of Geology, Volume 81, pages 381-405.

Morganti, J.
1988: Sedimentary-type stratiform ore deposits: some models and a new classification. *In* Ore Deposit Models. *Edited by* R.G. Roberts and P.A. Sheahan. Geoscience Canada, Reprint Series No. 3, pages 67-78.

Nunn, G.A.G., Noel, N. and Culshaw, N.G.
1984: Geology of the Atikonak Lake area, Grenville Province, western Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-1, pages 30-41.

Nunn, G.A.G., Emslie, R.F., Lefebvre, C.E., Noel, N. and Wells, S.
1986: The Atikonak River massif and surrounding area, western Labrador and Quebec. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 125-145.

Pearce, J.A. and Cann, J.R.
1973: Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth and Planetary Science Letters, Volume 19, pages 290-300.

Pearce, J.A. and Norry, M.J.
1979: Petrogenetic implications of Ti, Zr, Y and Nb variations in volcanic rocks. Contributions to Mineralogy and Petrology, Volume 69, pages 33-47.

Pyke, M.W.
1956: Report on exploration in areas G and K, Labrador, 1956. Unpublished report, BRINEX G56015, Newfoundland Department of Mines and Energy, Mineral Development Division, 13 pages. Open File [Lab 181]

Rona, P.A., Klinkhammer, G. Nelson, T.A., Tefry, J.H. and Elderfield, H.
1986: Black smokers, massive sulphides and vent biota at the mid-Atlantic Ridge. Nature, Volume 321, pages 33-37.

Ryan, B., Neale, T. and McGuire, J.
1982: Descriptive notes to accompany geological maps of the Grand Lake area, Labrador, 13F/10, 11, 14, 15. Newfoundland Department of Mines and Energy, Mineral Development Division, Maps 82-64 to 82-67, 14 pages.

Sawkins, F.J.
1976: Massive sulphide deposits in relation to geotectonics. *In* Metallogeny and Plate Tectonics. *Edited by* D.F. Strong. Geological Association of Canada, Special Paper 14, pages 221-240.

Schärer, U. and Gower, C.F.
1988: Crustal evolution in eastern Labrador; constraints from precise U−Pb ages. Precambrian Research, Volume 38, pages 405-421.

Schilling J.-G.
1973: Icelandic mantle plume: geochemical evidence along the Reykjanes Ridge. Nature, Volume 242, pages 565-571.

Schilling, J.-G., Zajac, M., Evans, R., Johnston, T., White, W., Devine, J.D. and Kingsley, R.
1983: Petrologic and geochemical variations along the mid-Atlantic ridge from 29°N to 73°N. American Journal of Science, Volume 283, pages 510-586.

Slack, J.F. and Shanks, W.C. III
1989: Geologic and isotopic characteristics of modern and ancient Besshi-type massive sulfide deposits. 28th International Geological Congress, Abstracts, Volume 3, page 3-132, Washington, D.C.

Smith, A.D. and Fox, J.S.
1989: Geochemistry of basalts from the Windy Craggy and Anyox volcanogenic massive sulphide deposits, British Columbia. Geological Association of Canada−Mineralogical Association of Canada, Program with Abstracts, Volume 14, page A22.

Sun, S.-S.
1980: Lead isotope study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs. Philosophical Transactions of the Royal Society of London, Volume 297, pages 409-445.

Sutton, W.R.
1965: Summary report of exploration during 1965. Sandwich Bay−Square Island Joint Venture area, southeast Labrador. Unpublished report for BRINEX, Newfoundland Department of Mines and Energy, Open File Lab(200).

1966: BRINEX, Eagle River area, Labrador, 5 DDH records. Unpublished report for BRINEX, Newfoundland Department of Mines and Energy, Open File 13H/11(1), 12 pages.

Swinden, H.S., Jenner, G.A., Fryer, B.J., Hertogen, J. and Roddick, J.C.M.
1990: Petrogenesis and paleotectonic history of the Wild Bight Group: an Ordovician rifted island arc in central Newfoundland. Contributions to Mineralogy and Petrology, Volume 85, pages 253-271.

Thomas, A., Nunn, G.A.G. and Krogh, T.E.
1986: The Labradorian Orogeny: evidence for a newly identified 1600 to 1700 Ma orogenic event in Grenville Province crystalline rocks from central Labrador. *In* The Grenville Province. *Edited by* J.M. Moore, A. Davidson and A.J. Baer. Geological Association of Canada, Special Paper 31, pages 175-189.

Thompson, G. Humphris, S.E., Schroeder, B., Sulanowska, M and Rona, P.A.
1988: Active vents and massive sulfides at 26°N (TAG) and 23°N (Snakepit) on the Mid-Atlantic Ridge. Canadian Mineralogist, Volume 26, Part 3, pages 697-711.

Winchester, J.A. and Floyd, P.A.
1977: Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology, Volume 20, pages 325-343.

Wood, D.A., Joron, J.-L. and Treuil, M.
1979: A re-appraisal of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings. Earth and Planetary Science Letters, Volume 50, pages 326-336.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 217-227

THE LAC JOSEPH TERRANE AND THE CHURCHILL FALLS TERRANE: STRUCTURAL AND METAMORPHIC RELATIONS, OSSOKMANUAN LAKE (NTS 23H/SW) AND LAC JOSEPH (NTS 23A/NW) MAP AREAS, GRENVILLE PROVINCE, WESTERN LABRADOR

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ABSTRACT

The Ossokmanuan Lake–Lac Joseph area of western Labrador contains parts of two, fault-bounded terranes that are of regional extent. The terranes consist primarily of ca. 1670-1620 Ma crust and were tectonically juxtaposed in the ca. 1000 Ma Grenville Orogeny. In the map area, the Churchill Falls Terrane contains granitoid rocks of the ca. 1650 Ma Trans-Labrador batholith and mafic rocks of the ca. 1430 Ma Shabogamo Intrusive Suite. The rocks contain Grenville-age amphibolite-facies metamorphic assemblages. In contrast, the Lac Joseph Terrane is composed of supracrustal rocks, gabbronorite and granitoid intrusive rocks subjected to high-grade metamorphism in the ca. 1700-1600 Ma Labradorian Orogeny. The rocks in the Lac Joseph Terrane display only minor effects of the Grenville Orogeny.

Kinematic indicators and relationships between structures and metamorphic minerals in ductile shear zones adjacent to the terrane boundary, indicate that the Lac Joseph Terrane was emplaced from the southeast-to-northwest over the Churchill Falls Terrane. The high strain developed under medium-grade (Grenville) conditions.

INTRODUCTION

OBJECTIVES AND PREVIOUS WORK

The 1990 field season involved 1:100,000-scale geological mapping of the Ossokmanuan Lake (23H/SW) and Lac Joseph (23A/NW) map areas in western Labrador (Figure 1). Mapping was mainly helicopter-supported and carried out from a base camp on the Labrador City–Churchill Falls section of the Trans-Labrador Highway. A minor portion of the field work was accomplished using ground traverses based from the Trans-Labrador Highway and from boat-supported camps on Lac Joseph and Ossokmanuan Lake.

This project constitutes part of a long-term, regional-scale mapping program, undertaken by the Labrador Mapping Section, that has involved the investigation of the geology of the Grenville Province in Labrador and, in particular, the area marginal to the Grenville Front. The objective of the 1990 survey was to conduct systematic mapping focused on structural and metamorphic relationships, and the nature of major, terrane-bounding shear zones.

The results of the survey are addressed in a regional context, emphasizing the similarities in rock types and pre-Grenvillian structural and metamorphic histories that exist between tectonically juxtaposed domains in the region. These similarities raise the problem of local usage of terrane terminology, which is firmly established from studies in Phanerozoic orogens. Alternative nomenclature for identifying the domains in the map area are discussed.

Parts of the area have been previously mapped by Wynne-Edwards (1961, 23H/W), Stevenson (1967, 23A) and Connelly (1988). The area is adjacent to that mapped by Nunn and Christopher (1983, 23H/SE), Nunn *et al.* (1984, 23A/NE), Connelly and Scowen (1987, 23A/SW and parts of 23B and 22P) and, Rivers (1985a, 23G/SE and, 1985b, 23H/NW).

REGIONAL SETTING

Investigations in southwest Labrador and adjacent parts of eastern Quebec have shown that the Grenville Province can be subdivided into a number of tectonically bounded terranes (Figure 2). These are defined on the basis of contrasting rock types, structural styles and ages of metamorphism, and separated by major, high-strain zones (Rivers, 1983; Rivers and Nunn, 1985; Rivers and Chown, 1986; Wardle *et al.*, 1986). The terranes, variably affected by the ca. 1700-1600 Ma Labradorian Orogeny (Nunn *et al.*, 1984; Nunn *et al.*, 1985; Thomas *et al.*, 1985; Thomas *et*

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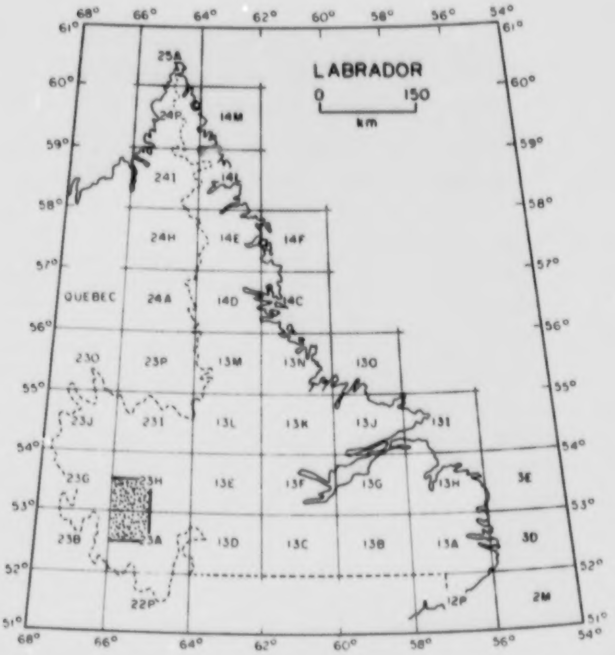

Figure 1. *Index map showing the location of the Ossokmanuan Lake–Lac Joseph map area (stippled area).*

al., 1986) and the ca. 1000 Ma Grenville Orogeny, have been proposed to be parautochthonous and allochthonous with respect to an autochthonous foreland represented by the Superior, Churchill and Makkovik provinces (Rivers and Chown, 1986).

The map area (Figure 3) contains parts of the Churchill Falls Terrane (Units 8 and 9) (Connelly and Nunn, 1988) and the Lac Joseph Terrane (Units 1 to 7) (Rivers and Chown, 1986); these consist mainly of ca. 1670-1620 Ma crust, although the Churchill Falls Terrane also contains mafic rocks of the Shabogamo Intrusive Suite (Rivers, 1980). Shabogamo gabbro, from west of the map area, has been dated at 1429 Ma (igneous age) by Connelly *et al.* (1990) using U–Pb (zircon) methods. The Churchill Falls Terrane and the Lac Joseph Terrane are from Rivers and Chown's (1986) parautochthonous and allochthonous zones, respectively.

The Lac Joseph Terrane and the Churchill Falls Terrane are separated by a zone of heterogeneously distributed ductile shear zones that extend for several kilometres on both sides of the boundary. An ensemble of kinematic indicators confirms that the Lac Joseph Terrane (upper structural-deck) was thrust to the northwest over the Churchill Falls Terrane (lower structural-deck). Connelly *et al.* (1990) have concluded that the Lac Joseph Terrane was emplaced on the terranes to the north between 1000 to 990 Ma based on $^{40}Ar-^{39}Ar$ geochronological studies.

To the west of the map area, the Lac Joseph Terrane is in tectonic contact with the Molson Lake Terrane (Connelly *et al.*, 1989), which is composed of metamorphosed 1645 Ma granitic rocks and Shabogamo gabbro. The Molson Lake Terrane and the Churchill Falls Terrane share the same structural position with respect to the Lac Joseph Terrane.

Results from U–Pb geochronology in the Lac Joseph Terrane have shown that the extensive high-grade metamorphism is Labradorian in age and that the Grenville effects are restricted to areas of low-grade retrogression (Connelly *et al.*, 1990). In contrast, Grenvillian metamorphism is significantly more pervasive in the Churchill Falls and Molson Lake terranes (Rivers and Nunn, 1985; Connelly and Nunn, 1988; Connelly *et al.*, 1989). Medium- to high-grade metamorphism of the Shabogamo gabbro and granitic rocks in the Churchill Falls Terrane and the Molson Lake Terrane is presumed to be Grenvillian. Grenvillian metamorphism also overprints Labradorian high-grade assemblages in supracrustal rocks in the Churchill Falls Terrane, east of the map area.

UNIT DESCRIPTIONS

LAC JOSEPH TERRANE

Paragneiss (Unit 1)

The oldest rocks in the Lac Joseph Terrane are high-grade migmatitic paragneisses (Unit 1). These rocks form a homogeneous and monotonous unit of pink- and grey-weathering gneisses derived from semipelitic to psammitic sediments. The rocks contain two, discordant phases of leucosome: an older, grey-weathering, finer grained phase and, a younger, pink-weathering, coarser grained phase. The percentage of leucosome in outcrops is varied, although it is generally greater than 40 percent. Locally, there are outcrop-scale areas where the paragneisses grade into homogeneous diatexite. The rocks commonly contain the high-grade assemblage: K-feldspar–biotite–sillimanite–garnet–magnetite. Connelly (personal communication, 1990) reports that kyanite occurs locally along the northern margin of the Lac Joseph Terrane. Orthopyroxene-bearing assemblages are suspected at several localities, although these remain to be confirmed by petrographic studies.

Within the paragneisses, boudins of structurally concordant, high-grade mafic rock and dark-green-weathering ultramafic rock, presumed to be deformed and metamorphosed mafic and ultramafic dykes, are common. Rarely, the paragneisses are interlayered with thin layers of quartz-rich foliate. (As defined by Ashton and Leclair (1990), a foliate is a foliated metamorphic rock without compositional layering and containing less than 50 percent platey grains that exhibit a parallel orientation.)

The high-grade paragneisses in the Lac Joseph Terrane are presumed to be correlative with the paragneisses that occur in the terranes to the east of the map area, including those in the Churchill Falls Terrane. Collectively, these paragneisses, named the Disappointment Lake gneiss by Thomas (1981), make up a continuous supracrustal belt that

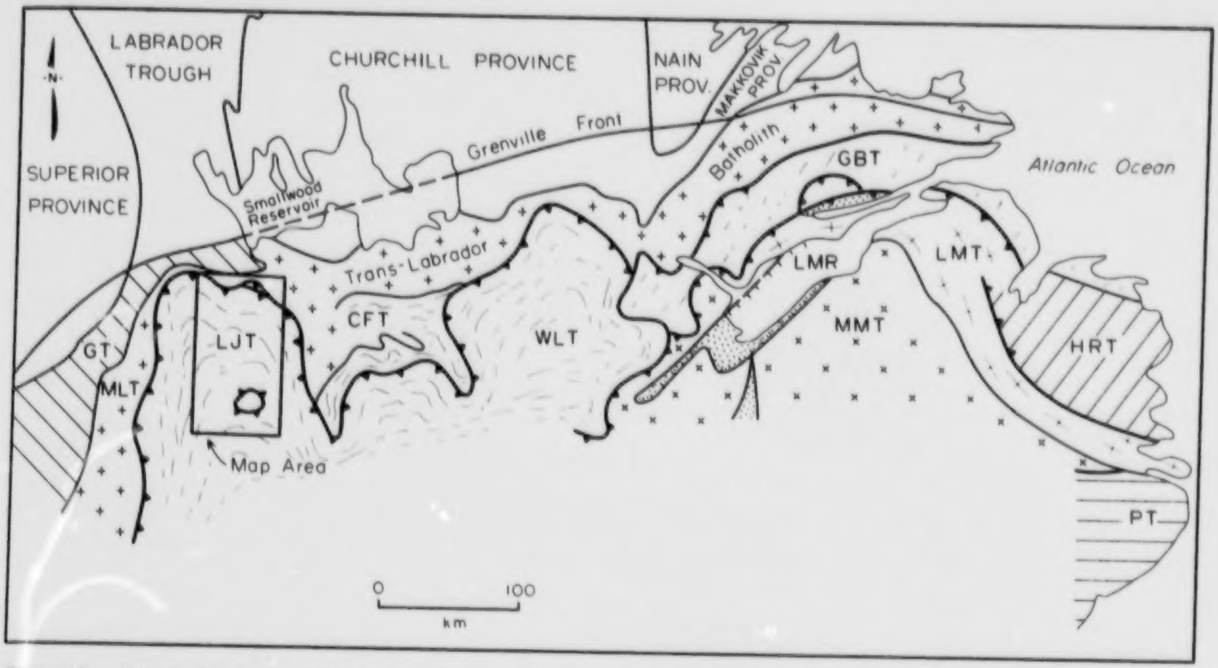

Figure 2. *Principal tectonic subdivisions of the Grenville Province, Labrador (modified after Wardle* et al., *1990). GT–Gagnon Terrane, MLT–Molson Lake Terrane, LJT–Lac Joseph Terrane, CFT–Churchill Falls Terrane, WLT–Wilson Lake Terrane, LMR–Lake Melville rift system, MMT–Mealy Mountains Terrane, GBT–Groswater Bay Terrane, LMT–Lake Melville Terrane, HRT–Hawke River Terrane, PT–Pinware Terrane.*

is at least 400 km long. The U–Pb geochronological studies of the paragneisses (Thomas *et al.*, 1986) yielded an age of 1676 Ma, suggesting that the sedimentary protolith is at least Early Proterozoic.

Heterogeneous Supracrustal Gneiss (Unit 2)

Interlayered with the paragneisses in the Lac Joseph area and north-northeast of Lac Joseph are mappable layers of a heterogeneous supracrustal gneiss (Unit 2). This unit is dominated by black- to rusty-weathering mafic gneiss having lesser amounts of intermediate-composition gneiss, pink and grey-weathering paragneiss, rusty paragneiss and quartz-rich foliate. The mafic gneisses are well-layered, two-pyroxene-plagioclase rocks that are migmatitic containing less than 30 percent tonalitic leucosome. These rocks are presumed to be derived from mafic and intermediate volcanic rocks, and interlayered semipelitic and quartzitic sediments.

Granitoid Gneiss (Unit 3)

Outcrops of pink, black and white-weathering granitoid gneisses that occur in a poorly defined body in the central part of the map area, and which occur as isolated outcrops throughout the paragneisses in the Lac Joseph Terrane, are defined as Unit 3.

The gneisses are varied in composition from outcrop to outcrop, from tonalitic to granitic and from relatively mafic, with hornblende, biotite and epidote, to relatively quartzofeldspathic. Garnet occurs in some outcrops. Gneissosity is defined by alternating mafic and quartzofeldspathic layers or by layers of granitoid leucosome.

The contact relationship between the granitoid gneisses and the supracrustal rocks is uncertain; however, it is assumed that these gneisses are derived from Labradorian-age granitoid plutonic rocks that were intruded into the supracrustal rocks.

Ossok Mountain Intrusive Suite (Unit 4)

The paragneisses of the Lac Joseph Terrane are intruded by large bodies and dykes/sills of variably deformed and recrystallized mafic intrusive rocks, here informally named the Ossok Mountain intrusive suite (Unit 4). These rocks are relatively well-exposed, especially in the area south and southwest of Ossokmanuan Lake and they underlie much of the topographically high areas in the Lac Joseph Terrane. Contacts between paragneiss (Unit 1) and the large mafic bodies (Unit 4) are gradational and, where they are relatively well-exposed, are marked by heterogeneous zones of paragneiss having a profusion of mafic dykes, and by mafic rocks containing abundant paragneiss xenoliths. On the map, the contact is placed where the proportion of mafic rocks is greater than paragneiss.

The unit has a homogeneous composition, predominantly gabbronoritic to gabbroic, and a minor amount of anorthosite. Occurrences of olivine gabbronorite are rare. Texturally, the

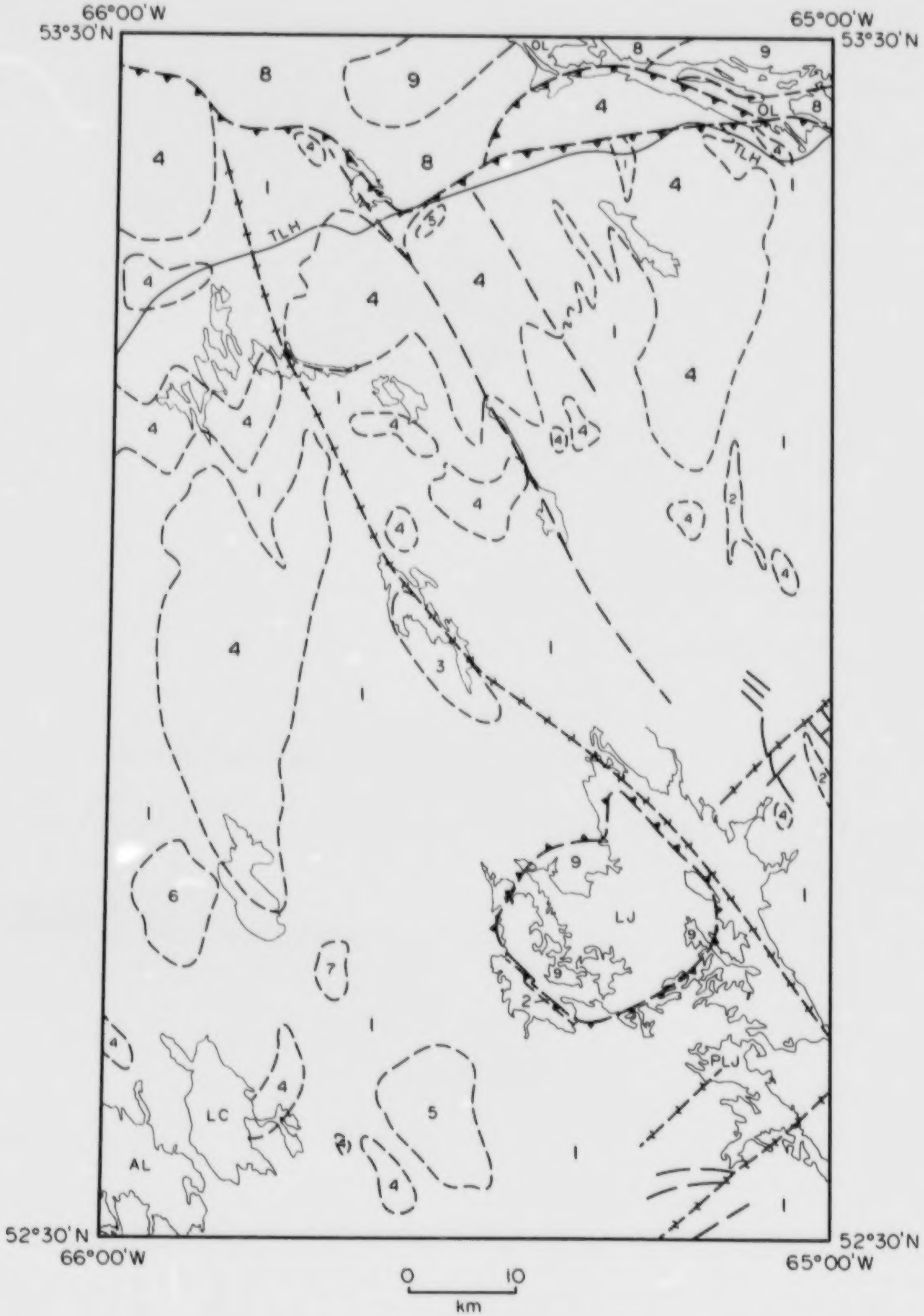
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Figure 3. *General geology of the Ossokmanuan Lake (NTS 23H/SW)–Lac Joseph (NTS 23A/NW) map area.*

Legend for Figure 3

CHURCHILL FALLS TERRANE (Lower Structural-Deck)

9 Shabogamo Intrusive Suite
gabbro, gabbronorite, coronitic gabbro

8 Trans-Labrador Batholith
megacrystic granite, granite, granitoid gneiss

LAC JOSEPH TERRANE (Upper Structural-Deck)

7 *quartz syenite*

6 *quartz monzonite, monzonite, monzodiorite*

5 *granite, megacrystic granite (locally rapakivi-textured)*

4 Ossok Mountain Intrusive Suite
gabbronorite, gabbro, mafic gneiss

3 *granitoid gneiss*

2 *mafic gneiss*

1 *paragneiss*

lithological contact

thrust fault (contact between the Churchill Falls and Lac Joseph terranes)

prominent topographic lineament

prominent break in the aeromagnetic pattern

OL-Ossokmanuan Lake, LJ-Lac Joseph, PLJ-Petit Lac Joseph, LC-Lac a l'Eau-Claire, AL- Ashuanipi Lake, TLH-Trans-Labrador Highway

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unit is very heterogeneous and is variable, even at the outcrop scale; from massive and coarse-grained having relict igneous textures to foliated, fine-grained and completely recrystallized. Relict cumulate layering, plagioclase lamination and rocks with relict intergranular textures are common. The wide textural variations are thought, at least in part, to reflect original textural variations between multiple intrusive phases that constitute the unit. The composite nature of the unit is clearly displayed in some outcrops where fine-grained, recrystallized and deformed gabbro dykes (having stable orthopyroxene) crosscut non-foliated, coarse-grained gabbronorite or cumulate layered rocks. Deformation and concomitant recrystallization appear to have occurred at granulite-facies conditions. There are also occurrences of undeformed but recrystallized dykes that intrude layered gabbronorite. These dykes are included in the Ossok Mountain intrusive suite. Similar undeformed dykes cut the metamorphic layering in the paragneisses.

Narrow (less than 1 km wide) zones of well-layered, mafic granulite gneisses occur around the margins of several of the gabbronorite bodies in the Lac Joseph Terrane. These rocks are included with the Ossok Mountain intrusive suite.

The U–Pb zircon geochronology by Connelly *et al.* (1990) of a coarse-grained gabbronorite from the Ossok Mountain intrusive suite (from west of the map area) gave an igneous age of 1.62 Ga.

Granitoid Intrusive Rocks (Units 5 to 7)

Dykes and small bodies of granitoid intrusive rocks intrude both the supracrustal rocks and rocks of the Ossok Mountain intrusive suite. The intrusive rocks include K-feldspar megacrystic granite, equigranular granite, quartz monzonite–monzonite–monzodiorite and quartz syenite. The contacts of the three granitoid bodies that occur in the southwestern part of the map area are poorly constrained and have been interpreted in part with the aid of 1":1 mile aeromagnetic maps (Geological Survey of Canada, 1973). The contact around the small body of granite in the northern part of the Lac Joseph Terrane is relatively well-constrained by outcrops.

Occurrences of K-feldspar megacrystic granite, locally rapakivi-textured, and equigranular granite are recrystallized and variably foliated (Unit 5). The textural variation from megacrystic to equigranular rocks is gradational on the outcrop scale. The rocks contain biotite. Orthopyroxene is suspected at several localities. Apart from the mapped bodies of granite, dykes of megacrystic and equigranular granite are common in the paragneisses and the Ossok Mountain intrusive suite, especially in the area immediately south of Ossokmanuan Lake, where highly strained sheets of megacrystic granite in the gabbronorite (Unit 4) are abundant.

The body of quartz monzonite–monzonite–monzodiorite (Unit 6) that occurs in the southwestern part of the map area is variably foliated and recrystallized. The rocks are fine- to medium-grained and contain hornblende. Locally, the body contains outcrops of megacrystic granite (Unit 5?), although the poor exposure prevents examination of the contact relationships.

The southwestern part of the map area also contains a small body of quartz-syenite (Unit 7). The rocks, which are pink- to mauve-weathering, fine- to medium-grained, non-foliated and phaneritic in texture, contain less than 10 percent fine-grained biotite and local clinopyroxene. The non-foliated and non-recrystallized character of this unit suggest that it is post-Labradorian.

Pink, coarse-grained, non-foliated and non-recrystallized pegmatites occur throughout the Lac Joseph Terrane. Commonly, the pegmatites contain muscovite and, where they intrude high-grade paragneisses, they may be surrounded by a muscovite halo that overprints high-grade assemblages in the country rock. Their unmetamorphosed and undeformed character suggest that these pegmatites are Grenvillian.

CHURCHILL FALLS TERRANE

Trans-Labrador Batholith (Unit 8)

Granitoid rocks in the Churchill Falls Terrane include variably foliated and recrystallized, equigranular and megacrystic granite and granitoid gneiss that are assigned to the Trans-Labrador batholith (as defined by Wardle *et al.*, 1986). Generally, these granitoid rocks are poorly exposed in the map area, although outcrops are somewhat more abundant southwest of Ossokmanuan Lake and on some of the islands in the lake. In areas with a paucity of outcrop, the contacts between the Trans-Labrador batholith (Unit 8) and the significantly more magnetic Shabogamo gabbro (Unit 9) have been interpreted with the aid of 1":1 mile aeromagnetic maps (Geological Survey of Canada, 1973).

The granitic rocks are varied in texture from fine- to medium-grained and equigranular to coarse grained, containing abundant K-feldspar megacrysts and local orbicular K-feldspar megacrysts. The textural relationship between the equigranular rocks and the megacrystic rocks appears to be gradational. The rocks commonly contain 5 to 10 percent biotite, and local muscovite, which is presumed to be a Grenvillian metamorphic mineral. The unit contains a subordinate amount of granodiorite.

The granitoid gneisses that are included with the Trans-Labrador batholith make up less than 30 percent of the unit in the map area. They consist of granitic, granodioritic and tonalitic gneiss and migmatite. Layering is defined by alternating mafic and quartzofeldspathic layers or by layers of grey-weathering leucosome. Biotite, in variable quantities, is the predominant mafic mineral present. At one location, the contact between gneiss and megacrystic granite, although not sharply defined, appears to be discordant to the gneissosity, suggesting that the gneisses are older than the granite.

The U–Pb zircon dates of Trans-Labrador batholith rocks indicate a ca. 1650 Ma age of emplacement (e.g., Brooks, 1983; Krogh, 1983; Thomas *et al.*, 1985; Nunn *et al.*, 1985; Connelly *et al.*, 1990).

Shabogamo Intrusive Suite (Unit 9)

The Trans-Labrador batholith is intruded by mafic rocks of the Shabogamo Intrusive Suite. The unit is composed of fine- to coarse-grained, massive to foliated gabbro and, locally, olivine gabbro. Relict cumulate layering and evidence of multiple intrusive phases are common. Locally, gabbros are gradational into coronitic gabbro in which the coronas consist of garnet around pyroxene, olivine or ilmenite. Garnet coronas are presumed to be a Grenvillian feature. The rocks may also have a poikiloblastic texture defined by abundant, 1- to 5-cm diameter garnets. Occurrences of gabbro and coronitic gabbro at Lac Joseph have been tentatively correlated with the Shabogamo Intrusive Suite in the Churchill Falls Terrane (after Connelly, 1988) on the basis of textural relations. The gabbro is interpreted to be exposed in a structural window through the Lac Joseph Terrane as opposed to an intrusion of Shabogamo gabbro into the paragneisses. There are no known intrusions of Shabogamo gabbro in high-grade, Labradorian paragneisses and a high-strain zone, which separates the gabbro from the paragneisses, supports this theory. A sample of the gabbro from Lac Joseph has been collected for U–Pb zircon geochronology and geochemical studies to test this model.

The gabbros at Lac Joseph are commonly massive, coarse-grained rocks having preserved igneous plagioclase and interstitial clinopyroxene. Locally, outcrops are cumulate layered. Garnet coronas occur around clinopyroxene and magnetite. Rarely, the unit includes well-layered mafic gneiss, mapped as part of the intrusive suite and xenoliths of black and rusty-weathering quartzofeldspathic gneiss containing biotite and garnet. The xenoliths are of uncertain origin. Outcrops may contain sets of undeformed, rectilinear pegmatite dykes.

STRUCTURE AND METAMORPHISM

LAC JOSEPH TERRANE

The paragneisses within the Lac Joseph Terrane are variably strained and can be observed in all states of a structural progression between two characteristic end-members. The lowest strained rocks are foliated gneisses that have open to tight, variably-plunging folds and refolded, Type 3 folds of the older leucosome and, lesser strained, discordant layers of the younger leucosome. The main biotite foliation is axial planar to the folds of the gneissosity. An older, locally preserved, biotite foliation that is folded with the gneissosity demonstrates that the main biotite foliation in most outcrops is at least the second generation of foliation in the paragneisses. In the highest strained end-member, both leucosomes are isoclinally folded, somewhat disrupted and completely transposed about the main biotite foliation. In both end-members, the main biotite foliation and the traces of axial planes of folds generally strike north-northwest to north-northeast. South of Lac Joseph, the main foliation is variable from north- to east-striking. Within the Lac Joseph Terrane, there is a random pattern of distribution between the lesser strained and the more highly strained paragneisses.

Locally, the main foliation and the metamorphic layering are openly folded about an approximately west-trending and steeply plunging fold axes. Folds may have a weak, axial-planar fabric defined by biotite. Because of the absence of retrogression, these structures are also presumed to be part of the high-grade deformation.

Sillimanite, present in most outcrops of paragneiss in the Lac Joseph Terrane, occurs as both fine- to medium-grained individual needles and needle-aggregates and, as medium- to coarse-grained, blue-grey, sillimanite-quartz nodules. Both varieties can occur either randomly oriented on the foliation surface, folded with the metamorphic layering, or lineated parallel to the fold axis. This suggests that growth of sillimanite occurred throughout the high-grade deformation. Kyanite occurrences in paragneisses are reported adjacent to the Lac Joseph Terrane–Churchill Falls Terrane boundary in the northern part of the map area (J. Connelly, personal communication, 1990). This suggests that there may be a south-to-north increase in metamorphic pressure and paleodepth toward the terrane boundary.

The U–Pb monazite geochronology by Connelly *et al.* (1990) has dated the two leucosomes in the paragneisses at 1645 Ma (grey phase) and 1635 Ma (pink phase), thus, the high-grade metamorphism and synchronous deformation in the Lac Joseph Terrane is entirely Labradorian.

The state of strain and the metamorphic assemblages in Ossok Mountain intrusive suite rocks and in the metamorphosed granitoid rocks are compatible with the Labradorian, high-grade assemblages and structures in the paragneisses. In the Ossok Mountain intrusive suite, recrystallized and variably foliated rocks contain the mineral assemblage: clinopyroxene–orthopyroxene–plagioclase and, local garnet. Fabrics in the granitoid rocks are defined by biotite or hornblende. Some outcrops of the megacrystic granite (Unit 5) may be orthopyroxene-bearing.

It is uncertain if the paragneisses were deformed prior to the intrusion of the Ossok Mountain intrusive suite. Local mafic dykes, which are undeformed but recrystallized under high-grade conditions, are discordant to structures and metamorphic layering in the paragneisses and the gabbronorite. This demonstrates that there are some post-main deformation mafic intrusive phases. This relationship also demonstrates that high-grade metamorphic conditions persisted past the end of the main Labradorian deformation.

Locally, rocks within the Lac Joseph Terrane are deformed by narrow (outcrop-scale), ductile, high-strain zones that strike from northwest to northeast. These shear zones cannot be traced from outcrop to outcrop and their regional significance is uncertain. Rocks within these shear zones are not retrogressed suggesting that these structures are late syn-(Labradorian) metamorphic.

In the field, the recognizable effect of Grenvillian metamorphism is the presence of local muscovite in paragneiss. Commonly, the muscovite-bearing rocks lack K-feldspar and sillimanite and have a distinctive black- and white-weathered appearance. With the exception of a few occurrences of deformed muscovite in highly strained paragneiss adjacent to the Lac Joseph Terrane–Churchill Falls Terrane boundary and around the tectonic window at Lac Joseph, muscovite is randomly oriented. The distribution of muscovite-bearing paragneiss is sporadic throughout the Lac Joseph Terrane, although occurrences are most common in a poorly defined, 1- to 15-km-wide zone around Lac Joseph. The retrogression may be related to concentration of Grenvillian strain along the Lac Joseph Terrane–Churchill Falls Terrane boundary.

The absence of significant, regional retrogression of the high-grade Labradorian assemblages is in agreement with U–Pb evidence that suggests that the Lac Joseph Terrane did not experience significant Grenville heating (Rivers and Nunn, 1985; Connelly *et al.*, 1990).

The Lac Joseph Terrane contains a conjugate set (?) of lineaments, striking 325° and 055°, that are defined by topographic lineaments and linear breaks in the aeromagnetic anomaly pattern. The northwest-striking set is the most prominent. Neither set of structures is known to displace lithological contacts, however, in most cases, given the limited outcrop control, contacts could be re-interpreted to show minor separations across these structures.

The most westerly of the northwesterly-striking structures is marked by a conspicuous aeromagnetic lineament and is at least 100 km long. Several outcrops of paragneiss that are located along the trace of this structure around the north end of Lac Joseph contain medium- to high-grade, steeply east-dipping, ductile shear zones. At one location, C/C' structures indicate an east-side-down kinematic sense (i.e., normal displacement), however, the paucity of kinematic indicators and the uncertainty in the temporal correlation between the structures in outcrop and the aeromagnetic break, hinder any definitive interpretation of this structure.

THE CHURCHILL FALLS TERRANE

The ages of the fabrics and the metamorphic layering in the Trans-Labrador batholith are equivocal. The U–Pb sphene dates reported by Rivers and Nunn (1985) from the

Churchill Falls Terrane indicate metamorphic ages between 1000 and 990 Ma, although there could still be older, Labradorian assemblages and structures preserved in the Trans-Labrador batholith. The Grenvillian metamorphism in the area reached amphibolite facies (Rivers and Nunn, 1985) and may have been high enough to produce migmatites in the Churchill Falls Terrane (Nunn and Christopher, 1983). Geothermobarometry from the Churchill Falls and Molson Lake terranes (Connelly and Nunn, 1988; Connelly *et al.*, 1989) indicates that the Grenvillian metamorphic pressures were significantly higher than Labradorian pressures and that temperatures reached 750°C in the Molson Lake Terrane.

The ductile, high-strain zones that obliterate older foliations and layering in the granitoid rocks are inferred to be Grenvillian structures related to Lac Joseph Terrane–Churchill Falls Terrane juxtaposition. This correlation is based on similarity of attitudes between the high-strain zones and the Lac Joseph Terrane–Churchill Falls Terrane boundary. Local muscovite may be a product of medium-grade, medium- to high-pressure Grenville-age metamorphism or late-Grenville retrogression.

Locally, gabbro and garnet-coronitic gabbro of the Shabogamo Intrusive Suite are foliated and mylonitized. These structures are restricted to zones that are marginal to the Lac Joseph Terrane–Churchill Falls Terrane boundary and, like the high-strain zones in the Trans-Labrador batholith, are also judged to be related to Grenvillian terrane juxtaposition. The high-strain zones deform amphibolite-facies garnet coronas that were formed in the Grenvillian Orogeny (Rivers and Mengel, 1987) demonstrating that the high-strain cannot be older than the peak of Grenville metamorphism. Outside of the high-strain zones the state of strain in the gabbro and coronitic gabbro is very low.

THE LAC JOSEPH TERRANE–CHURCHILL FALLS TERRANE BOUNDARY

The rocks adjacent to, and on both sides of, the Lac Joseph Terrane–Churchill Falls Terrane boundary are cut by heterogeneously distributed, ductile high-strain zones that strike parallel to the terrane boundary and are presumed to be related to juxtaposition. The boundary itself is not exposed and where outcrops are scarce, its position has been inferred from aeromagnetic data.

Within the Lac Joseph Terrane in the Ossokmanuan Lake area, the high-strain is concentrated within layers of megacrystic granite and paragneiss that are (tectonically?) interlayered with gabbronorite. In most cases, rocks in these high-strain zones apparently preserve their high-grade, Labradorian assemblages with only local retrogression in the paragneisses and mafic rocks. The retrogressed paragneisses contain variably deformed muscovite and the mafic rocks are retrogressed to amphibolite facies having deformed hornblende and plagioclase defining the high-strain structures. These relations suggest that high-strain in the Lac Joseph Terrane, in zones contiguous with the Lac Joseph Terrane–Churchill Falls Terrane boundary, occurred at medium-grade.

South of Ossokmanuan Lake, strain is heterogeneously distributed, although ductile, high-strain is locally concentrated along a zone that is interpreted to be a splay from the main Lac Joseph Terrane–Churchill Falls Terrane boundary. Exposure in the area is limited, however, it appears that the high-strain may be concentrated in a narrow zone of mylonitic paragneiss that is coincident with a significant topographic lineament and aeromagnetic break.

Ductile high-strain zones within the Churchill Falls Terrane, presumed to be related to Lac Joseph Terrane–Churchill Falls Terrane juxtaposition on the basis of orientation and structural-metamorphic relations, deform Trans-Labrador batholith rocks and Shabogamo gabbro. Although limited in number, an ensemble of kinematic indicators from gabbro, including C/C' structures, rolled feldspar porphyroclasts and tails, asymmetric folds and the margin-to-centre variation in foliation attitude across shear zones, demonstrates a southeast over northwest (i.e., thrust) sense of transport. The apparent stability of the coronitic assemblage in the highly strained gabbro also suggests that strain occurred under medium-grade conditions that may have been relatively close to the peak conditions of Grenvillian metamorphism in this area.

Similar structural and metamorphic relationships in Lac Joseph Terrane and Churchill Falls Terrane rocks occur around the margin of the inferred tectonic window at Lac Joseph. Highly strained and retrogressed paragneisses, mafic supracrustal gneisses and coronitic Shabogamo gabbro having amphibolite-facies assemblages demonstrate that Grenvillian strain in the Lac Joseph area proceeded under medium-grade conditions.

ECONOMIC GEOLOGY

Previously reported mineralization is restricted to occurrences of disseminated pyrite within gabbroic rocks and, disseminated chalcopyrite and pyrite at the Wynne Showing (UTM coordinates 365450 E, 5865900 N; Newfoundland Department of Mines and Energy, 1976). Mapping in 1990 has also revealed several occurrences of disseminated pyrite in the gabbronoritic and gabbroic rocks and the supracrustal rocks in the Lac Joseph Terrane. Several of the more notable gossans occur in gabbronorite at 334550 E, 5885250 N and, 355100 E, 5919300 N and, in supracrustal rocks at 334050 E, 5885250 N (UTM coordinates). Although these showings are only minor, the layered gabbronoritic and gabbroic rocks have potential for PGE mineralization and the supracrustal rocks have some potential for preserving sediment-hosted massive sulphide mineralization.

Meyer (1989) reports occurrences within the map area of muscovite-bearing pegmatites intersected by road construction at kilometre 90 and kilometre 137 (measured from Labrador City) on the Trans-Labrador Highway. These occurrences may have potential for high-quality sheet muscovite.

DISCUSSION

One of the more notable results from the mapping is that the Trans-Labrador batholith has been recognized to extend continuously from the Churchill Falls Terrane (east of the map area) into the Molson Lake Terrane (west of the map area). The structural continuity of the batholith around the northern margin of the Lac Joseph Terrane suggests that the Churchill Falls Terrane and the Molson Lake Terrane are the same pre-Grenville tectonic entity and that they occupy the same structural and tectonic position with respect to the Lac Joseph Terrane. Linkage between the Molson Lake Terrane and the Churchill Falls Terrane has also been proposed by Connelly *et al.* (1989).

Another regional lithological correlation can be made between terranes. High-grade Labradorian paragneisses within the Churchill Falls Terrane, east of the map area, are interpreted to be correlative with the high-grade paragneisses in the Lac Joseph Terrane on the basis of composition (Rivers and Nunn, 1985). This correlation and the present structural disposition of the terranes suggest that the Lac Joseph Terrane and the Churchill Falls Terrane represent two structural decks of a structurally telescoped, but once lithologically continuous pre-Grenville terrane that was composed principally of ca. 1670 to 1620 Ma crust. The absence of both voluminous granitoid intrusions and Shabogamo gabbro in the Lac Joseph Terrane can be explained if the Lac Joseph Terrane originally lay to the present-day southeast of both the main part of the Trans-Labrador batholith and the most southerly intrusions of Shabogamo gabbro. This implies a minimum displacement on the Lac Joseph Terrane–Churchill Falls Terrane boundary in the order of 100 km, assuming that the displacement was consistently from southeast to northwest.

These lithological correlations illustrate that there are significant pre-Grenville similarities between the parautochthonous and allochthonous zones of Rivers and Chown (1986). These similarities, also recognized by Rivers and Nunn (1985) and Connelly and Nunn (1988), raise the problem of usage of terrane terminology and the term allochthonous (see definitions of terrane by Berg *et al.*, 1978; Jones *et al.*, 1983; and in the AGI Glossary of Geology, Bates and Jackson, 1987 and; allochthonous terrane by Howell and Jones, 1983). Perhaps to avoid problems with the firmly established definitions of terrane and allochthonous terrane, the word terrane could be replaced by lithotectonic zone or block or structural deck, depending on the lithological and structural relationships between neighbouring terranes and within terranes.

The Lac Joseph Terrane and the Churchill Falls Terrane have some differences in their geological histories. One of these differences is the disparate nature of Grenvillian metamorphism in the terranes. The medium-grade and high-pressure Grenville-age metamorphism in parts of the Churchill Falls Terrane (Rivers and Nunn, 1985; Connelly *et al.*, 1989) may be related to the emplacement of the Lac Joseph Terrane (Connelly and Nunn, 1988), although this raises the problem of how the Lac Joseph Terrane almost completely escaped Grenvillian metamorphism and penetrative strain. The absence of significant Grenville-age features could be explained if the Lac Joseph Terrane were emplaced at a relatively high crustal level where rocks were relatively cold and dry and, thus, not amenable to new (Grenville) mineral growth and concomitant development of penetrative mineral fabrics, except in the high-strain zones at the structural base of the Lac Joseph Terrane. Alternatively, Grenville-age metamorphism may have occurred in the Churchill Falls Terrane prior to emplacement of the Lac Joseph Terrane, which may have arrived relatively late and did not significantly contribute to the tectonic loading of the Churchill Falls Terrane.

The structural and metamorphic relationships in mylonitic rocks along the Lac Joseph Terrane–Churchill Falls Terrane boundary in the map area indicate that Grenvillian juxtaposition occurred under medium-grade conditions that were probably near the peak conditions of Grenvillian metamorphism for this area. This suggests that the former model might best explain the Grenville-age differences between the Lac Joseph Terrane and the Churchill Falls Terrane.

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REFERENCES

Ashton, K.E. and Leclair, A.D.
1990: Foliate: a useful term to complement the textural classification of foliated metamorphic rocks. Canadian Journal of Earth Sciences, Volume 27, pages 1095-1097.

Bates, R.L. and Jackson, J.A.
1987: Glossary of Geology, Third Edition, American Geological Institute, 788 pages.

Berg, H.C., Jones, D.L. and Coney, P.J.
1978: Map showing pre-Cenozoic tectonostratigraphic terranes of southeastern Alaska and adjacent areas. U.S. Geological Survey Open File Report 78-1085.

Brooks, C.
1983: Fourth report on the geochronology of Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File [Lab 519], 32 pages.

Connelly, J.N.
1988: An investigation of the margin of the Lac Joseph Allochthon, Grenville Province, southwestern Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, p 37-48.

Connelly, J.N. and Nunn, G.A.G.
1988: Relationships between the Lac Joseph Allochthon and underlying terranes, southwestern Labrador. Geological Association of Canada, Annual Meeting, Program With Abstracts, St. John's 1988, page A24.

Connelly, J.N. and Scowen, P.
1987: Geology of the Lac Caopacho−Lac Fleur-de-May area, southwestern Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 225-235.

Connelly, J.N., Heaman, L. and Krogh, T.E.
1990: U−Pb geochronology and the evolution of the Grenville Province of western Labrador. Geological Association of Canada, Annual Meeting, Program With Abstracts, Vancouver 1990, Volume 15, page A26.

Connelly, J.N., van Gool, J. and Rivers, T.
1989: Molson Lake Terrane, a new terrane in the parautochthonous belt of the Grenville Province in southwestern Labrador. Geological Association of Canada, Annual Meeting, Program With Abstracts, Montreal 1989, Volume 14, page A23.

Geological Survey of Canada
1973: 1":1 mile-scale aeromagnetic maps for NTS 23A/11, A/12, A/13, A/14 and NTS 23H/3, H/4, H/5, H/6. Geological Survey of Canada, Maps 5963G, 5962G, 6003G, 6002G, 6013G, 6012G, 6053G and 6052G.

Howell, D.G. and Jones, D.L.
1983: Tectonostratigraphic terrane analysis and some terrane vernacular. *In* Proceedings of the Circum-Pacific Terrane Conference. *Edited by* D.G. Howell, D.L. Jones, A. Cox and A.M. Nur. Stanford University Publications, Geological Sciences, Volume XVIII, pages 6-9.

Jones, D.L., Howell, D.G., Coney, P.J. and Monger, J.W.H.
1983: Recognition, character, and analysis of tectonostratigraphic terranes in western North America. *In* Accretion Tectonics in the Circum-Pacific Region. *Edited by* M. Hashimoto and S. Uyeda. Tokyo, Terra, pages 21-35.

Krogh, T.E.
1983: Report on U−Pb sphene geochronology, Labrador and Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File [Lab 708], 79 pages.

Meyer, J.
1989: Graphite, mica and heavy-mineral sands exploration in Labrador. *In* Report of Activities for 1989. Newfoundland Department of Mines and Energy, Geological Survey Branch, pages 11-12.

Newfoundland Department of Mines and Energy
1976: Mineral Occurrence Tables, Labrador, Open File Lab 326, 94 pages, (accompanies Mineral Occurrence Map of Labrador, Map 761).

Nunn, G.A.G. and Christopher, A.
1983: Geology of the Atikonak River area, Grenville Province, western Labrador. *In* Current Research, Part A. Geological Survey of Canada Paper 83-1A, pages 363-370.

Nunn, G.A.G., Noel, N. and Culshaw, N.G.
1984: Geology of the Atikonak Lake area, Grenville Province, western Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-1, pages 30-41.

Nunn, G.A.G., Thomas, A. and Krogh, T.E.
1985: The Labradorian Orogeny: geochronological data base. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 43-54.

Rivers, T.
1980: Revised stratigraphic nomenclature for Aphebian and other rock units, southern Labrador Trough, Grenville Province. Canadian Journal of Earth Sciences, Volume 17, pages 668-670.

1983: The northern margin of the Grenville Province in western Labrador−anatomy of an ancient orogenic front. Precambrian Research, Volume 22, pages 41-73.

1985a: Geology of the Wightman Lake area, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 85-28.

1985b: Geology of the Gabbro Lake area, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 85-26.

Rivers, T. and Chown, E.H.
1986: The Grenville Orogen in eastern Quebec and western Labrador—definition, identification and tectonometamorphic relationships of autochthonous, parautochthonous and allochthonous terranes. *In* The Grenville Province. *Edited by* J.M. Moore, A. Davidson and A.J. Baer. Geological Association of Canada, Special Paper 31, pages 30-50.

Rivers, T. and Mengel, F.C.
1987: Contrasting assemblages and petrogenetic evolution of corona and noncorona gabbros in the Grenville Province of western Labrador. Canadian Journal of Earth Sciences, Volume 25, pages 1629-1648.

Rivers, T. and Nunn, G.A.G.
1985: A reassessment of the Grenvillian Orogeny in eastern Quebec and western Labrador. *In* The Deep Proterozoic Crust in the North Atlantic Provinces. *Edited by* A.C. Tobi and J.L.R. Touret. Reidel Publishing, NATO Advanced Science Institute Series, Volume 158, pages 163-174.

Stevenson, I.M.
1967: Geology of the Lac Joseph map area (23A), Newfoundland and Quebec. Geological Survey of Canada Paper 67-62, 4 pages.

Thomas, A.
1981: Geology along the southwestern margin of the Central Mineral Belt. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 81-4, 40 pages.

Thomas, A., Nunn, G.A.G. and Wardle, R.J.
1985: A 1650 Ma orogenic belt within the Grenville Province of northeastern Canada. *In* The Deep Proterozoic Crust in the North Atlantic Provinces. *Edited by* A.C. Tobi and J.L.R. Touret. Reidel Publishing, NATO Advanced Science Institute Series, Volume 158, pages 151-161.

Thomas, A., Nunn, G.A.G. and Krogh, T.E.
1986: The Labradorian Orogeny: Evidence for a newly identified 1600-1700 Ma orogenic event in Grenville Province crystalline rocks from central Labrador. *In* The Grenville Province. *Edited by* J.M. Moore, A. Davidson and A.J. Baer. Geological Association of Canada, Special Paper 31, pages 175-190.

Wardle, R.J., Rivers, T., Gower, C.F., Nunn, G.A.G. and Thomas, A.
1986: The northeastern Grenville Province: new insights. *In* The Grenville Province. *Edited by* J.M. Moore, A. Davidson and A.J. Baer. Geological Association of Canada, Special Paper 31, pages 13-29.

Wardle, R.J., Crisby-Whittle, L.V.J. and Blomberg, P.
1990: Geology of the Minipi River area (NTS 13C/NW). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 267-276.

Wynne-Edwards, H.R.
1961: Geology. Ossokmanuan Lake (west half), Newfoundland. Geological Survey of Canada, Map 17-1961.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 229-230

NAIN–NUTAK AREA: A NEW 1:500,000-SCALE COLOUR COMPILATION

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ABSTRACT

A 1:500,000-scale full-colour map of the Nain–Nutak region has recently been published by the Geological Survey Branch. The map incorporates the results of 48 years work in the region by E.P. Wheeler II, augmented with data collected, since 1970, by various government and university research groups. It displays the various stratigraphic subdivisions of the gneissic and plutonic rocks, and is the first in a series of similar maps to be published during the next few years.

BACKGROUND

The Nain–Nutak area had been the geological focus of E.P. Wheeler II from 1926 until his death in 1974. This incredible record, of 48 years of research, was directed mainly toward the anorthositic rocks that are spectacularly exposed along the coast and on the adjacent plateau between Nain and Okak Bay. Dr. Wheeler's legacy to later workers in the area includes a series of 1:63,360-scale maps covering nearly all the known extent of the batholitic polyphase igneous terrane now known as the Nain Plutonic Suite. Copies of these maps are filed at the Department of Geology and Geography, University of Massachusetts, Amherst, Massachusetts, and at the Geological Survey Branch, Department of Mines and Energy, St. John's. These hand-drawn manuscript maps were compiled at 1:200,000 scale by A. Harris at the Department of Mines and Energy in 1980, and released as a two-colour series in 1984.

Between 1971 and 1981, detailed studies in the Nain area (under the umbrella of the Nain Anorthosite Project led by Dr. S.A. Morse of the University of Massachusetts) built further upon the foundation laid by E.P. Wheeler. As a consequence, modifications to Wheeler's pioneering work became necessary. The more detailed studies on selected parts of the Nain Plutonic Suite resulted in an informal and formal stratigraphic nomenclature appearing in the geological literature.

Between 1985 and 1989, regional 1:100,000-scale transects from the coast to the Labrador–Quebec border were carried out in the Voisey Bay area by the Newfoundland Department of Mines and Energy (B. Ryan) and in the Nutak (Okak Bay) area by the Geological Survey of Canada (GSC) (I. Ermanovics). These surveys expanded upon the 1:250,000-scale reconnaissance mapping of F.C. Taylor (GSC) conducted in the early 1970's, and they led to the definition of an informal nomenclature for regional subdivisions of the Archean and Proterozoic gneisses. These surveys also led to the recognition of several structurally and stratigraphically distinct zones within gneisses of the Nain–Nutak region.

PURPOSES OF NEW MAP

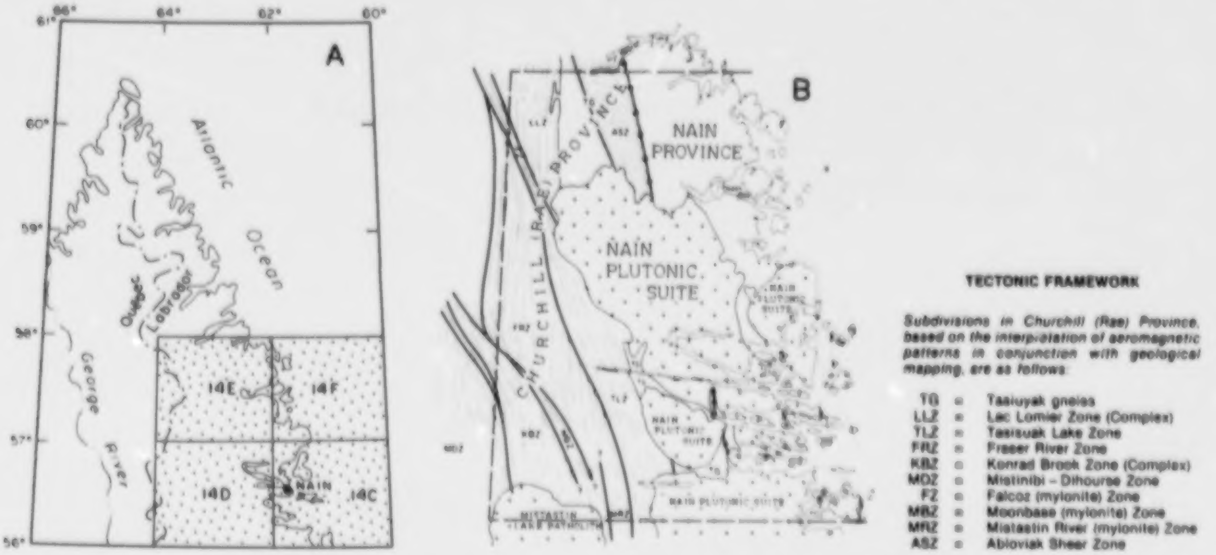
The Newfoundland Department of Mines and Energy has now released a preliminary 1:500,000-scale colour map (see Figure 1), which incorporates all work carried out in the Nain–Nutak area up to 1989. The map serves several purposes:

1. It is a testimony and dedication to the pioneering efforts of the late E.P. Wheeler II, whose leg-work provided the basis for all subsequent surveys. The distribution of rock units within the Nain Plutonic Suite are largely those shown on Wheeler's manuscript maps, with modifications to reflect the changes brought about by subsequent work.

2. It brings together the results of years of work by a group of geologists who have focussed on individual aspects of the area. In this regard, it summarizes the results of Canadian and American investigators in a manner that allows the latest interpretations of regional relationships to be shown.

3. It shows for the first time the major subdivisions of the gneissic and plutonic terranes, and incorporates the stratigraphic nomenclature commonly employed in references to the area. This permits the user to immediately see a specific unit referred to in the literature in relation to others around it.

4. It is the first published map to show the regionally recognizable four-component igneous assemblage that constitutes the Nain Plutonic Suite, a world-famous example of an anorogenic magmatic terrane. The regional distribution of the anorthositic, troctolitic, ferrodioritic and granitic rocks is shown, as determined from E.P. Wheeler's maps and subsequent studies. Modifications are probably still necessary here, since some of Wheeler's 'buff-weathering anorthosite' has been mapped by subsequent workers as ferrodiorite. However, the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SUITE
CHURCHILL (RAE) PROVINCE
NAIN PLUTONIC SUITE
MISTASTIN LAKE BATHOLITH
LLZ
ASZ
FRZ
TLZ
KBZ
MBZ
MDZ
TECTONIC FRAMEWORK
Subdivisions in Churchill (Rae) Province, based on the interpretation of aeromagnetic patterns in conjunction with geological mapping, are as follows:
TG = Tasiuyak gneiss
LLZ = Lac Lomier Zone (Complex)
TLZ = Tasisuak Lake Zone
FRZ = Fraser River Zone
KBZ = Konrad Brook Zone (Complex)
MDZ = Mistinibi - Dihourse Zone
FZ = Falcoz (mylonite) Zone
MBZ = Moonbase (mylonite) Zone
MRZ = Mistastin River (mylonite) Zone
ASZ = Abloviak Shear Zone

Figure 1. *a) Dotted area shows the four 1:250,000 NTS sheets covered by the Nain–Nutak map. b) Map outlining the major tectonostratigraphic units portrayed on the Nain–Nutak compilation, with the divisions within the Churchill Province shown.*

map still allows the distribution of the plutonic rocks to be seen, and allows generalized comments regarding areal abundance of each rock type.

5. The map is meant to provide a basis and focus for continuing work in the region because much of the information portrayed on it has been previously available only to a small and widely dispersed group of individuals, actively involved with ongoing work in the area. Some of the contacts between the map units are based on aeromagnetic data and on the extrapolation of known contacts and relationships. The validity of these interpretations have to await further work.

6. It represents the first in a planned series of 1:500,000-scale map sheets to be published prior to the production of the next geological map of Labrador. Such maps will provide a synthesis of all government, industry and university geological mapping in Labrador at the time of their publication.

ACKNOWLEDGMENTS

The compilation of the Nain–Nutak sheet was expedited by help from R.F. Emslie, I.F. Ermanovics, M.A. Hamilton, S.A. Morse and R.A. Wiebe. Technical assistance was rendered by the Cartographic Staff of the Geological Survey Branch. All are thanked for their contributions.

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NEW PERSPECTIVES ON THE NAIN PLUTONIC SUITE AND ITS COUNTRY ROCKS

Bruce Ryan
Labrador Mapping Section

ABSTRACT

The archipelago east of Nain comprises a variety of Archean quartzofeldspathic gneiss, foliated granitoid rocks, metasedimentary gneiss and mafic gneiss, intruded by plutonic rocks of the Middle Proterozoic Nain Plutonic Suite (NPS). Emplaced into the Archean rocks is a swarm of diabase dykes, of at least three generations, which exhibit a variety of intrusive forms and a variable degree of metamorphism and deformation. A younger set of dykes that intrudes the NPS is fresh and undeformed. Field data suggest that both the Archean rocks and older dyke swarm have been subjected to post-dyke granulite-facies (pyroxene hornfels) metamorphism. Problems raised by the tectonized state of the dykes are discussed in relation to the regional geological framework of the Nain area. It is suggested that these dykes are, in part, related to the basic magmatism of the NPS because such dykes also intrude recrystallized and deformed plutonic rocks considered to be early members of the NPS.

Reconnaissance examination of the NPS west and north of Nain has shown that the plutonic rocks have been subjected to pervasive penetrative deformation and subsequent recrystallization. Present models on emplacement of the NPS ascribe such deformation to primary magmatic flow and 'stretching' within crystal mushes during diapiric emplacement. An alternative viewpoint presented here is that the fabrics and recrystallization represent post-emplacement processes within crystalline rocks, generated by zonal deformation and annealing in a high heat-flow environment.

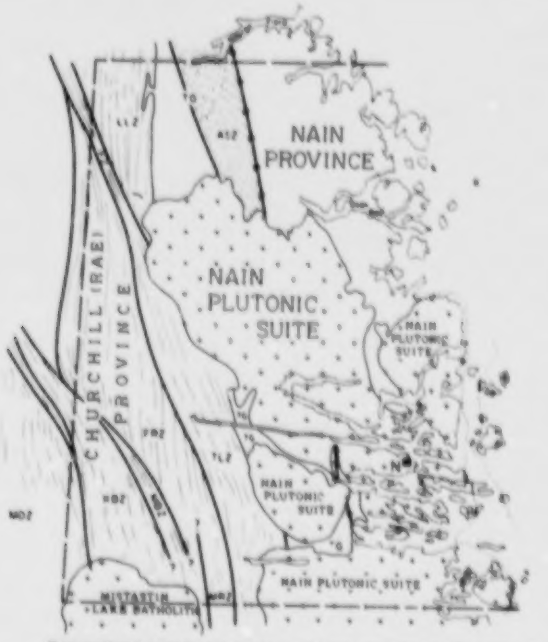
A model is presented to account for the features observed in the metamorphosed mafic dykes and NPS around Nain. It is proposed that many of the mafic dykes in the gneisses are a result of 'leaking' from a mafic magma reservoir that was the precursor of the main NPS event. Rise of NPS plutons to their present crustal levels, in an environment of episodic extensional shear and continued dyke emplacement, contributed to the metamorphism and deformation of the dykes in the gneisses and in early plutons.

INTRODUCTION

The Nain area has been a focus of interest for geologists for over two centuries, spurred mainly by the superb coastal exposures of labradorite-bearing anorthositic rocks. This interest was initially aroused by the discovery of 'Labrador stone' near Nain by the Moravian missionaries in 1770 (cf. de Waard, 1969). Studies of the Nain area formed the backbone of E.P. Wheeler's research between 1948 and 1974 (cf. Wheeler 1942, 1960; Emslie *et al.*, 1972) and resulted in an impressive series of 1 in. = 1 mile unpublished manuscript maps covering the area from Davis Inlet north to Okak, which are on file with the Department of Geology and Geography, University of Massachusetts, and with the Geological Survey Branch, Department of Mines and Energy (see Ryan, *this volume*). This pioneering work provided the impetus for a concentrated examination of anorthosite genesis by S.A. Morse and his colleagues under the Nain Anorthosite Project (NAP) between 1971 and 1981 (cf. Morse, 1971-1983). The focussed investigations of the anorthosite and associated plutonic rocks, now collectively known as the Nain Plutonic Suite (NPS), revealed a diversity of compositions (ultramafic, noritic, troctolitic, anorthositic, granitic), differing intrusion forms (e.g., small bulbous bodies, saucer-shaped layered intrusions, large dykes), and the existence of multiple intrusive events within superficially simple plutonic units. The ten-year NAP, especially, went a long way to elucidating some of the major problems associated with the emplacement and petrogenetic development of the NPS and anorthositic rocks in general. The NPS is now cited as a classic example of Middle Proterozoic anorogenic magmatism (cf. Morse, 1982).

The gneissic country rocks, into which the NPS was emplaced, have received less attention than the igneous rocks. Wheeler's initial mapping (cf. Wheeler, 1942, 1955, 1960, 1969) provided some of the first descriptions of these rocks. He recognized a major compositional difference between the gneisses of the eastern coastal sector and those of the western interior uplands, a distinction eventually used by Taylor (1979) as one of his criteria for the separation of Archean and Proterozoic gneisses into the Nain and Churchill structural provinces. Wheeler (1955, 1969) also recognized some contact metamorphism of gneisses adjacent to the Nain Plutonic Suite.

De Waard (1971) was the first to focus specifically on the gneisses of the Nain area, concluding that those on eastern Paul Island and adjacent areas were largely metamorphosed sedimentary rocks. He termed these gneisses the Ford



Generalized trends based on regional aeromagnetic patterns.

TECTONIC FRAMEWORK

Subdivisions in Churchill (Rae) Province, based on the interpretation of aeromagnetic patterns in conjunction with geological mapping, are as follows:

TG = Tasiuyak gneiss
LLZ = Lac Lomier Zone (Complex)
TLZ = Tasisuak Lake Zone
FRZ = Fraser River Zone
KBZ = Konrad Brook Zone (Complex)
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FZ = Falcoz (mylonite) Zone
MBZ = 'Moonbase' (mylonite) Zone
MRZ = Mistastin River (mylonite) Zone
ASZ = Abloviak Shear Zone

Figure 1. *Major tectonostratigraphic subdivisions of central and coastal Labrador (from Ryan, 1990). The north-trending area enclosed by the dotted lines east of Nain (N) is the septum of Archean gneisses that was the main focus of the 1990 field program. See Figure 2 for areas examined.*

Harbour Formation, and proposed that their present characteristics were largely attained after intrusion of nearby anorthositic plutons, a conclusion later challenged by Wheeler and Morse (1973). The gneisses of the Ford Harbour area have been examined most recently by Bridgwater *et al.* (1990), who attempted correlation of these rocks with the Archean gneisses of the Saglek area to the north and the Hopedale area to the south.

The specific studies of the Nain area cited above, and other investigations of northern Labrador geology up to 1990 (cf. Wardle *et al.*, *in press*), have led to regional subdivisions and a relative chronology of events, which, in simplified form is summarized below. This summary will serve as a foundation for later discussion in this paper.

REGIONAL GEOLOGY

Early to Late Archean (3.8 to 2.7 Ga) gneisses and less-deformed granitoid rocks constitute the Nain Province. The Nain Province was intruded by an areally extensive basic dyke swarm between 2300 to 2100 Ma and, following a period of peneplanation, was overlain by Lower Proterozoic supracrustal sequences. The Nain Province was juxtaposed against the Churchill Province (Proterozoic and reworked Archean gneiss) during Early Proterozoic transpressional orogenesis, along the collisional Abloviak shear zone (Figure 1). The Abloviak shear zone is in part co-incident with the Tasiuyak gneiss, a distinctive garnet-rich paragneiss and anatexite forming most of the easternmost margin of Churchill Province. The Nain gneisses, the basic dykes, and the supracrustals were deformed and metamorphosed adjacent to easternmost Churchill Province. The effects of the Early Proterozoic collision wane eastward across Nain Province. Lower Proterozoic tectonism appears to have abated by 1750 Ma. The boundary zone between the Nain and Churchill provinces was punctured during the Middle Proterozoic by batholithic masses of basic to felsic rock, collectively referred to as the anorthosite–mangerite–charnockite–granite (AMCG) suite (cf. Emslie and Hunt, 1990), of which the Nain Plutonic Suite is one example (Figure 1). Geochronological investigations of several units within the NPS indicate that at least some of the igneous activity occurred at ca. 1325 to 1290 Ma. This magmatism is advocated to have taken place during an anorogenic phase of crustal evolution of this area, possibly concomitant with limited crustal extension. The NPS was subsequently intruded by at least two suites of compositionally distinct, fresh, undeformed diabase dykes, possibly of Middle Proterozoic age (Wiebe, 1985), but some may be as young as Tertiary (Bridgwater *et al.*, 1990).

PROBLEMS DEFINED IN THE NAIN AREA

The 1990 field work in the Nain area (Figure 2) has revealed that its geological history may include events not recognized in the chronology presented above. In particular, as outlined below, observations call for a re-evaluation of the metamorphic evolution of the Archean gneisses and an explanation for deformed and metamorphosed dykes within them. Data from the 1990 field season also point to strong deformation and recrystallization in the NPS. The observations are especially relevant to present models of NPS emplacement, most of which portray the plutons themselves as being undeformed, and which advocate that the emplacement mechanism imposed only restricted metamorphic and structural imprints on the surrounding rocks.

This paper, then, will focus on the main points raised above. In terms of the problems that they bring to light, the 1990 field results may be stated as follows:

(i) Metamorphosed and deformed basic dykes have been found to be widespread in the gneisses on the archipelago east of Nain but their age and origin are uncertain; (ii) dykes with similar attributes intrude deformed noritic plutons akin to the NPS but it is unclear if these plutons are really a part of the NPS, or possibly belong to the country-rock gneiss complex; and (iii) north and west of Nain there are large areas of deformed and recrystallized anorthositic and granitic rocks within the NPS; the character of such rocks seems anomalous for plutons intruded in an anorogenic (non-stressed) environment.

It is now apparent that the Nain area may contain some of the most exciting geological problems in Labrador. In order to set the scene for the results of this year's survey, a short overview of previous work and ideas is presented at the beginning of some of the sections to follow.

NAIN PROVINCE GNEISSES AND THEIR METADIABASE DYKES

PREVIOUS WORK

It has been noted above that the gneisses of the Nain Province in the region around Nain have not received any detailed examination, except for the localized studies of de Waard (1971) and Bridgwater *et al.* (1990) in the area of eastern Paul Island. De Waard (1971) suggested that all the gneisses were derived from 'a eugeosynclinal pile of clastic sediments, volcanics and ultramafic rocks', and he termed them the Ford Harbour Formation. He proposed that their present high-grade and multiple-folded state was a consequence of events accompanying emplacement of an anorthositic pluton to the west; prior to emplacement of this intrusion, the Ford Harbour Formation was only mildly folded. This interpretation was not favoured by Wheeler and Morse (1973), who correctly pointed out that the character of the Ford Harbour gneisses is not unlike other Archean rocks of coastal Labrador, regardless of proximity to anorthosite, and therefore, the features of the Ford Harbour rocks are pre-anorthosite. Bridgwater *et al.* (1990) disagreed with de Waard's interpretation of the Ford Harbour gneisses as being largely of supracrustal origin, noting that, although there were obvious supracrustal components within them, these gneisses are in fact polygenetic, and include a significant component of layered grey orthogneiss and late pegmatite sheets. They considered the Ford Harbour gneisses to be akin to, and a continuation of, the Early to Middle Archean gneisses of the Okak–Saglek area of northern Labrador.

One of the most obvious features of the coastal outcrops of gneisses on the islands east of Nain is the diabase dyke swarm. These 'trap rocks' have been noted by all the pioneering geologists who have sailed along the Labrador coast (cf. Daly, 1902) but only Wheeler (1933) attempted to subdivide them. He recognized four types, based on mineralogy and degree of 'autometamorphism', and considered them all to be the same age and to have originated from a single magma by differentiation. Upton (1971, 1974) conducted a cursory field and geochemical examination of some of the dykes during the NAP, and seems to have been the first to recognize the presence of both metamorphosed (amphibolite) and unmetamorphosed types; the amphibolite dykes were considered to pre-date intrusion of the NPS (Upton, 1971). His geochemical investigation of the fresh dykes showed that both a tholeiitic and an alkalic suite are present. More recently, Wiebe (1985) has examined the fresh dykes that intrude the anorthositic rocks around Nain. The overall composition of the dykes examined by Wiebe (1985) is alkalic, but he subdivided them into two groups based on high and low incompatible-element contents, especially P_2O_5.

De Waard (1971, p. 16), Berg and Briegel (1983, p. 44) and Bridgwater *et al.* (1990, p. 232 to 233), like Upton (1971), also recognized that many of the dykes in the gneiss complex are metamorphosed and recrystallized to varying degrees. They also recognized that the dykes were locally deformed. De Waard (1971) offered no explanation for these characteristics of the dykes; Berg and Briegel (1983) felt that some of the dykes were related to the NPS; Bridgwater *et al.* (1990), following Upton (1971), considered the metamorphosed dykes in their study area on Paul Island to pre-date the nearby anorthositic pluton, but also stated that some dykes may be related to NPS magmatism.

REGIONAL SUBDIVISIONS OF THE GNEISSIC ROCKS

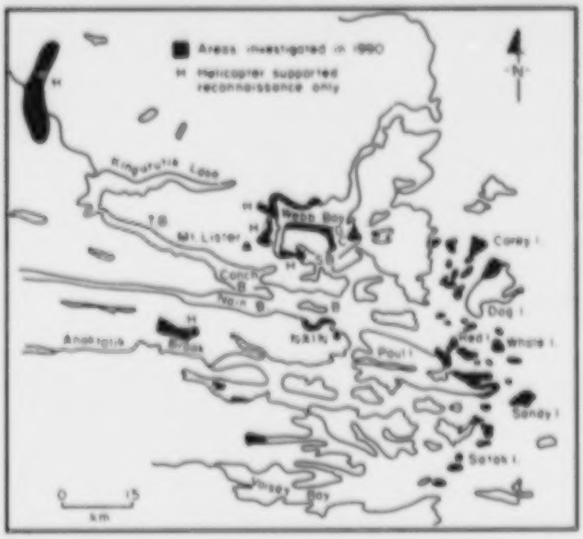
The gneissic rocks east of Nain comprise a north-trending septum between igneous rocks of the NPS (Figure 1). They are well-exposed on the archipelago that typifies the Labrador coast of this region, and were examined by the author on the islands between Carey Island and Sungilik Island (Figures 2 and 3). The Archean bedrock in this area comprises a variable suite of orthogneiss and foliated granitic (s.l.) rocks, metasedimentary gneiss, and mafic gneiss.

Quartzofeldspathic Gneiss and Foliated Granitic Rocks

These can be subdivided into several regionally recognized units. Predominant among them are the following:

Migmatized Tonalitic to Granodioritic Gneisses

These are by far the most abundant gneiss type, and vary from white to grey to brownish grey, the latter indicating rocks


Areas investigated in 1990
H Helicopter supported reconnaissance only
N
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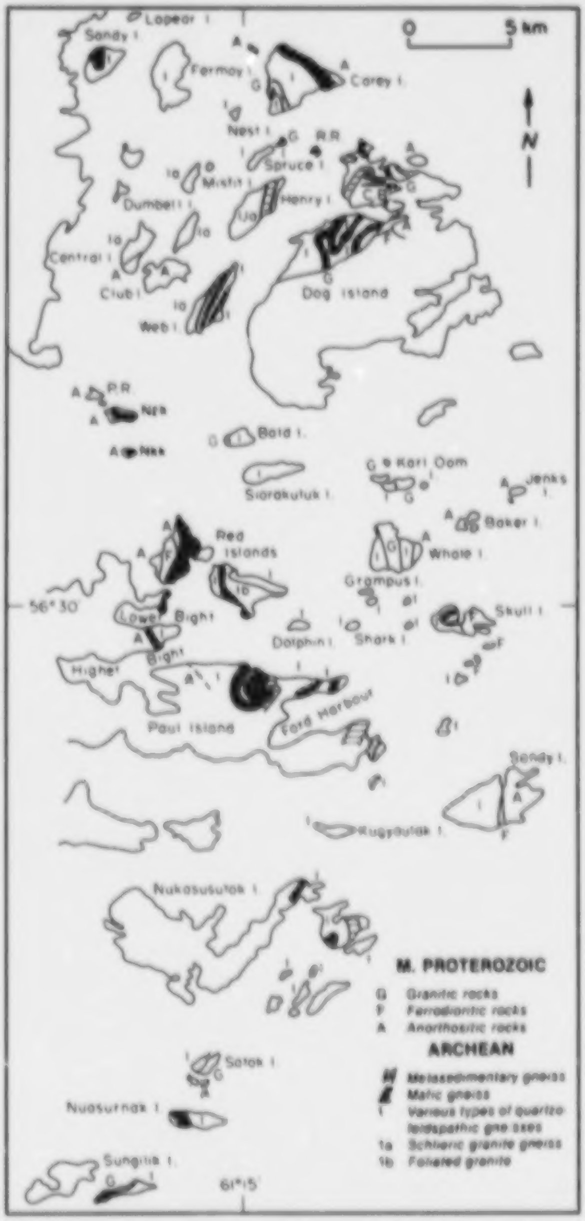
Mt Lister
Webb Bay
S.B.
Conch B
Nain B
B
Anaktalak
NAIN
Paul I
Carey I
Dog I
Red I
Whale I
Sandy I
Satok I
Whisky Bay
0 15
km

Figure 2. *Location map, showing in black, areas examined during the 1990 field season. T.B. = Tikkoatokak Bay, S.B. = Sachem Bay, B = Barth Island, C = Challenger Cove, G = Georges Island.*

are in the granulite facies of metamorphism. They are the predominant rock on northern Sandy Island, Lopear Island, Fermoy Island, Carey Island, Nest Island, Spruce Island and Dog Island (Figure 3). The migmatized polyphase character of these gneisses is best seen in areas where they are at amphibolite facies (Plate 1). In areas where granulite-facies metamorphism is still preserved, such as the west shore of Dog Island south of 'Camp Bay', the different quartzofeldspathic components are less distinct.

Whispy Granitoid Gneiss

The well-layered and migmatitic gneisses are intruded by a more diffusely banded and foliated polyphase granitoid varying from granodiorite through diorite in composition; locally this unit is porphyritic. Sheets of this type of whispy granitoid occur as subordinate lit-par-lit injections in grey gneiss on Lopear Island and the northeast coast of Fermoy Island. Limited examination of Henry Island suggests that sheets of this granitoid may comprise 50 percent of the western half of the island as well. It is the dominant rock type on Misfit Island, Dumbell Island, Central Island and the western half of Web Island (Figure 3), where screens of older gneiss containing pre-granite structure are locally present. Contacts between the various phases of this whispy granitoid are generally very diffuse (Plate 2); only contacts between melanocratic and leucocratic phases are sharp. In places, the whispy granitoid gneiss contains metamorphosed basic dykes that may be a product of coeval mafic magmatism (see later section on dykes). The lit-par-lit nature of this polyphase granitoid to the migmatitic gneisses on an outcrop to regional scale, combined with the diffuse layering and anastomosing style of the mineral fabric is suggestive of syntectonic emplacement.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Sandy I
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Spruce I
Misfit I
Dumbell I
Henry I
C.B.
Central I
Club I
Web I
Dog Island
P.R.
Nzk
Nkk
Bald I
Siorakuluk I
Kari Oom
Jenks I
Baker I
Red Islands
Whale I
Grampus I
56°30'
Lower Bight
Dolphin I
Shark I
Skull I
Higher Bight
Paul Island
Ford Harbour
Sandy I
Kugyaulak I
Nukasusutok I
Satok I
Nuasurnak I
Sungilik I
61°15'
M. PROTEROZOIC
G Granitic rocks
F Ferrodioritic rocks
A Anorthositic rocks
ARCHEAN
Metasedimentary gneiss
Mafic gneiss
1 Various types of quartzofeldspathic gneisses
1a Schlieric granite gneiss
1b Foliated granite

Figure 3. *Simplified geological map of the area between Carey Island and Sungilik Island. Only the largest regional units are shown. R.R. = Red Rocks, C.B. = 'Camp Bay', P.R. = Pat Rocks, Nzk = Noazunaluk Island, Nkk = Noazunakuluk Island.*

White to Pink Foliated Granitoid Rocks, Probably More than One Generation

These vary from the above in being more homogeneous overall, with a mineral foliation being the chief fabric-forming element. Narrow sheets of white-weathering leucogranite occur on Dog Island but the largest coherent area of these

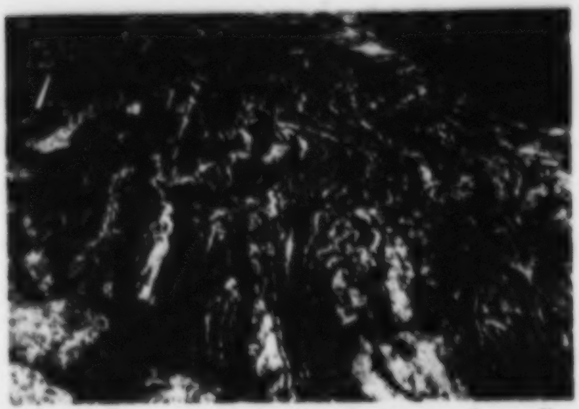

Plate 1. *Grey migmatite in area of retrogressed granulite-facies rocks, south of Grampus Island.*

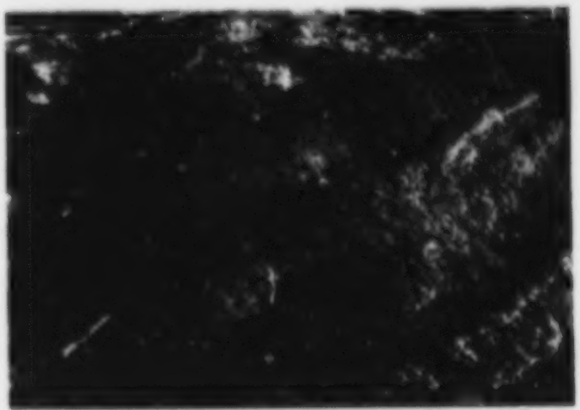

Plate 2. *Whispy granitoid gneiss, Misfit Island. Note the streaky compositional layering and folded contacts between light and dark phases in top half of photo.*

rocks forms the heart of East Red Island (Figure 3). The East Red Island granite varies from massive to weakly foliated, and from medium grained to aplitic. Pink potassium feldspar phenocrysts are locally present; a small area of similar porphyritic rock occurs on northern Paul Island. The East Red Island granite locally contains abundant older gneissic rafts and it is clearly intrusive into the mafic granulites as well as the quartzofeldspathic gneisses on the island. A rusty-weathering tinge suggestive of orthopyroxene-bearing assemblages is present in some places but no pyroxene could be identified in the field.

Pink, Potassic, Medium-Grained and Aplitic Granite Sheets

These rocks are marked by a biotite foliation and/or lineation, and are quite distinct units on West Red Island. It is an extensive area of this granite at the north tip of the island that gives rise to the geographic designation of that area as Red Cliff. These granitoids all occur as steeply dipping sheets slightly transgressive to the regional gneissosity of the mafic granulite and gneiss. Several of them on the southeast promontory of the island have veins of massive milky quartz and quartz-microcline graphic pegmatite developed within their central parts. Like the East Red Island granitoid, these pink granitoids also have a brownish hue suggestive of the presence of orthopyroxene. De Waard (1971) implies from his description of these rocks that they are melts generated by emplacement of the adjacent Proterozoic anorthositic rocks, but this writer suggests they may be instead an integral part of the pre-anorthosite complex.

Granulite-Facies Quartzofeldspathic Gneisses of Various Types

Granulite-facies gneisses predominate in the region southward from the Red Islands. For example, nebulitic quartzofeldspathic granulite-gneiss is widespread on the north shore of East Red Island and Dolphin Island. Schlieric granitoid to pegmatite-layered granulitic gneisses underlie the islands east of Nukasusutok Island (Figure 3) where they plainly intrude and disrupt older supracrustal sequences. These schlieric granulites give rise to agmatite zones in which the layering in the blocks commonly has random orientation with respect to external fabrics in the quartzofeldspathic host. Orthopyroxene crystals are readily identifiable in these rocks, but commonly these gneisses have a blebby characteristic, a result of orthopyroxene replacement by secondary minerals. *In situ* partial melt phenomena are local features in the granulite-facies gneisses; these are diffuse-bordered irregular and vein-like networks of orthopyroxene- (and lesser garnet-) bearing granitoid that disrupt the layering. Lit-par-lit migmatite, in which a grey brown foliated component is 'diluted' by pegmatoidal to aplitic orthopyroxene-bearing sheets, is well developed locally around Ford Harbour and on some of the islands east of Nukasusutok Island. In the latter area, these sheets postdate at least one period of earlier migmatization of the gneisses.

Granulite-facies gneisses also occur around Webb Bay (Figure 2). These rocks, part of the Webb Valley metamorphic complex of Berg (1973), were examined only briefly along the coast. A difference in these, compared to elsewhere, is that some of the parallel mafic layers and pods within them have plagioclase crysts, suggesting a comparison with one type of mid-Archean Saglek dyke of northern Labrador.

Metasedimentary Gneisses

Gneisses of metasedimentary origin are not common in the Archean terrane of the outer islands mapped to date; however, several discrete belts or zones of migmatized paragneiss have been outlined, occurring on Henry Island, Dog Island, and on Paul Island (Figure 3). Paragneisses have also been observed elsewhere, but are not as extensive or have not been fully outlined. These occur on Carey Island, the Karl Oom Islands, Grampus Island, on the headland on the south side of Ford Harbour, on Kugyautak Island and on the cluster of islands east of Nukasusutok Island.

Dominant among the paragneisses is biotite-rich rusty-weathering garnetiferous semipelite; locally there is abundant sillimanite and graphite. Garnet and sillimanite are variably replaced by combinations of cordierite + hypersthene and cordierite + spinel respectively, a pseudomorphous replacement that is attributed to pyroxene hornfels facies contact metamorphism by the plutonic rocks in the area. The replacement reaction is also seen in garnet-bearing granitoid sheets and irregular melt pods in the gneisses.

Quartzite is particularly prominent in paragneisses examined south of Dog Island. Grampus Island for instance is composed almost entirely of migmatized white quartzite and greenish-grey calcareous quartzite. Quartzites of this type also occur on the south side of Ford Harbour. Rusty sulphide-bearing dark-grey quartzite is common in a belt on the east coast of the large island east of Nukasusatok Island; here it forms large blocks, in association with ultramafic rocks, in an agmatite zone caused by intrusion of the adjacent quartzofeldspathic gneisses and pegmatites.

Mafic Gneisses

Mafic gneisses, mapped as both amphibolite and mafic granulite, are common in the area; the largest units are shown on Figure 3. Two discrete types are present, one of which may be intimately related to the anorthositic rocks.

The first is a massive to well-layered, black, commonly friable rock, interpreted to be derived from a gabbroic protolith. It is locally characterized by conspicuous blasts and segregations of black hornblende (Plate 3). Leucocratic layers are not uncommon, and sub-parallel and randomly oriented white granitoid sheets locally disrupt the layering. This type of rock outcrops for instance on Naozunaluk Island, through the centre of West Red Island, on the southern point of East Red Island and forms much of the prominent ridge 3 km west-northwest of Ford Harbour on Paul Island (Figure 3). At the latter locality it contains several orange-red dunitic units.

The second type of mafic granulite is well displayed on the eastern side of Carey Island and on the north shores of Lower Bight and Higher Bight on Paul Island. In all the localities mentioned above, the rocks are greenish brown to black weathering, well-layered and characterized by the presence of elongate 'stringers' and podiform pyroxene aggregates (Plate 4). Disrupted pods and segregations of norite are also present, and have been cited by Wiebe (1981, 1990) as examples of anorthosite dykes. Intrafolial folds of the compositional layering may be present, as well as slides of the layering with dislocation surfaces slightly oblique to layering trend. At Higher Bight, the noritic segregations and pods are both folded with the layering and also are emplaced along the axial-plane trend of these same folds. Mapping to date of the Carey Island granulite has indicated that several ultramafic bodies occur along its western margin.

The second type of mafic granulite maybe in part related to the adjacent noritic rocks, but if not, has certainly been 'soaked' by narrow noritic dykes that have been subsequently disrupted and deformed. Wheeler (manuscript maps) regarded some rocks of this type as 'granulites of uncertain origin', an apt name for such enigmatic units. At least some rocks of this type contain olivine (M.A. Hamilton, personal communication, 1990), a mineral that, from this writer's experience elsewhere in Labrador, is present only in the ultramafic portions of mafic granulite units within the Archean terrane. The occurrence of olivine here suggests that rocks in which it occurs should be included with the adjacent igneous suite. Therefore, these 'granulites' may represent early layered basic intrusions of the NPS, punctured later by the more massive noritic rocks. R.F. Emslie (personal communication, 1990) and G.A.G. Nunn (personal communication, 1990) have both observed rocks of this type along the margin of the Michikamau intrusion in western Labrador; these rocks pose similar problems of interpretation but are favoured to be of igneous origin by both Emslie and Nunn. Carey Island offers a good area to study these rocks in detail.

Plate 3. *Blotchy mafic granulite, East Red Island. Black spots are hornblende blasts. Probably derived from an original gabbroic protolith.*

Plate 4. *Layered mafic granulite, Carey Island. Darker layers are ultramafic in composition. Note the streaky concentration of pyroxene in lower centre, and dislocation surface at lower right.*

ATTRIBUTES OF THE RECRYSTALLIZED AND DEFORMED MAFIC DYKES

The profusion of mafic dykes, of at least four generations is one of the most noteworthy features of the field area. They pose some of the more intriguing problems of the area, particularly with regard to their diversity, degree of deformation and metamorphism/recrystallization. The following observations will give a brief overview of these features, which, without the benefit of petrography at this time, are based on field data only. It must be borne in mind that insufficient data are available to state that any one feature described below is unique to a particular age or trend of dyke. Therefore, the features are treated in very general terms, with the hope that future work on the dykes may characterize them more fully. Of the four generations of dykes recognized, three exhibit variable degrees of recrystallization and deformation; these are collectively referred to as metadiabase dykes and are described in this section. The fourth generation of dykes comprises fresh diabase and gabbros; these are described in a subsequent section.

The metadiabase dykes are rarely absent from any region underlain by gneisses although they are less common on the Red Islands than in other areas. They also occur in deformed plutons that bear strong similarities to the more pristine igneous rocks of the NPS (see below). They are nearly everywhere recrystallized and foliated, their primary pyroxenes appear to be largely replaced by secondary pyroxene aggregates and amphibole, and they locally exhibit folding that varies from gentle warps to nearly isoclinal structures. Some of the dykes are granoblastic rocks that were given the field designation 'granulite-facies dykes'; it is possible that these are noritic rocks in which the orthopyroxene is a primary mineral. This problem will hopefully be solved by petrography.

There are few mesoscopic features of the dykes that correlate with trend, and there is no firm correspondence between trend and relative age. The latter point can be demonstrated on eastern Fermoy Island, for instance, where two massive amphibolite dykes trending approximately 160° are temporally separated by another dyke trending 080° (Plate 5); this makes relative age designations among the isolated 160°-trending dykes somewhat risky. The overall trend of the dyke swarm as a whole is in fact quite variable, and may be consistent or widely disparate over small areas. The majority of the metadiabases on Dog Island for instance trend 070 to 090°, yet on Misfit Island they vary from 000 through 090 to 170°. However, that being the case, there is a tendency for certain trends to predominate. An approximation of relative orientations, based on some 150 measurements, indicates 71 percent of the dykes trend between 000 and 090°, with nearly half of these falling between 060 and 090°.

Only a few general observations on the dykes are given below, without any rigorous attempt at correlating their age of intrusion. A few examples of crosscutting dykes are cited as an indication of relative age at any one locality, but as noted above, these ages cannot be applied to isolated dykes.

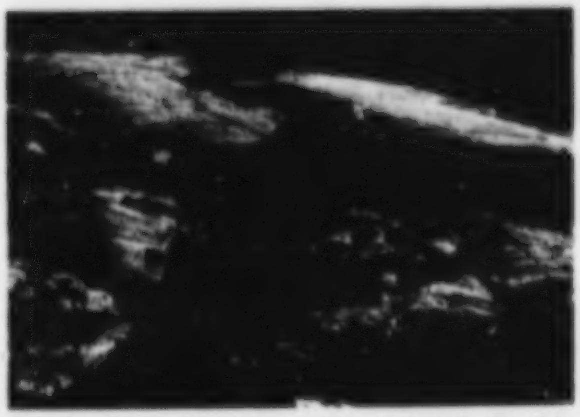

Plate 5. *Intersecting dykes on Fermoy Island. The dyke trending across the photo is older than the dyke trending away from the viewer. At the water's edge the latter dyke is cut by a younger dyke with the same trend as the older dyke of this photo, but the youngest dyke cannot be seen due to slope of outcrop. The slight warp in the trend of the younger dyke in the photo may be a primary feature; this dyke is characterized by radial aggregates of tabular plagioclase (snowflake texture).*

General Morphology

The metadiabase dykes vary from a few centimetres to 20 m in width and, where examined, are generally strike-continuous for hundreds of metres; extrapolation of some dykes between opposite coasts of islands indicate that some are continuous for at least 2 km. For the most part they are rectilinear bodies, but mild undulations in strike direction are not uncommon. At some localities (e.g., Dumbell Island, East Red Island) it appears that dykes having highly discordant trends are in fact part of the same intrusive event. These may be interpreted as being emplaced into conjugate fracture systems, but there is little evidence that such a conjugate series of dykes is widespread. On Dumbell Island, the bifurcating dykes crosscut an earlier set of dykes and are in turn cut by a younger set.

The vast majority of the metadiabases are equigranular fine- to medium-grained, fairly homogeneous rocks. Discrete chilled margins are not always present, but are conspicuous on some, especially the wider dykes. They are overwhelmingly metabasaltic in character, though two composite dykes are present on western Misfit Island, one of which exhibits what appear to be deformed incipient mafic pillows adjacent to a grey granitic component.

Original igneous textures in the dykes are locally well preserved though the igneous minerals are either replaced by secondary assemblages or polygonized by the metamorphism. For instance several, feldspar-phyric, 070- to 090°-striking black troctolitic(?) dykes exposed on the eastern and southern parts of Fermoy Island are characterized by abundant clusters or aggregates of buff to white recrystallized plagioclase lathes. Many of these clusters have a radial or snowflake-like configuration of feldspars and they enclose pyroxene. Although superficially resembling the plagioclase form in feldspar spherulites (snowflakes) described elsewhere in the NPS by Berg (1980), a direct correlation between the shape and origin of the aggregate textures in the dykes here, and those described by Berg from troctolitic intrusions to the north, cannot be confidently proposed at this time. However, if these are metamorphosed troctolitic dykes and the radial textures are related, it implies that there are some troctolite magmas that were emplaced fairly early in this area and all such intrusions are not a 'late' event (cf. Morse, 1983a). This conclusion is based on the fact that these 'snowflake' dykes are at one locality on the east side of the island intruded by a younger massive mafic dyke and both are subsequently recrystallized. At the southern tip of the island the 'snowflake' dykes are intruded by a folded massive dyke.

Another textural variation noted at several widely spaced localities is the presence of conspicuous, large, dark grey to black plagioclase phenocrysts in the dykes. These phenocrysts are identical to the dark plagioclase of the noritic and troctolitic intrusions of the NPS, again suggesting that some of the metadiabases are an integral part of the NPS magmatic episode as proposed by Berg and Briegel (1983).

The dykes exhibit a number of features that may hold clues to their mode of emplacement. These will be outlined below as an indication of the variety of intrusion forms to be seen in the dykes. They are described in the following order: marginal contacts, terminal contacts and podiform structure. Foliation development and the relationship between structures in the gneisses and dykes will be noted where necessary, but will be discussed more fully in a section to follow.

As noted above, the majority of dykes are rectilinear intrusions with sharp contacts against the gneisses. Not all contacts are straight however; many are cuspate. Cusp-and-lobe features are not extreme. Usually they are gentle structures and may be present only on one margin of a dyke (Plate 6). However, where cusp-and-lobe structure is well developed, the cusps are formed by the mafic dyke whereas the more gentle lobes are occupied by gneiss. This is, of course, the normal relationship seen where dykes are deformed along with the enclosing rock in such a way that the dykes are shortened parallel to their length (cf. Jackson and Zelt, 1984). In such situations, the dyke is less competent than the gneiss, and thus the cusp represents the area where the dyke gets 'nipped-in' between the more open-fold structure of the gneissic lobe. However, there is no indication that the features in the metadiabases described here are produced by such a mechanism, for nowhere have foliations been observed as axial-planar features in such cuspate contacts. In fact, where fabrics are developed they are generally parallel to the dyke trend, i.e., perpendicular to the axial trend of the lobe-and-cusp features. Therefore, the lobe-and-cusp margins are primary features developed during dyke intrusion. The cusp-and-lobe relationships are, however, opposite to the normal situation seen in segmented or finger-like mafic dykes intruded into more competent hostrocks (cf. Nash, 1979; Pollard, 1987). Therefore, it is suggested that the lobe-and-cusp characteristics displayed by the dykes of the Nain area are a function of their emplacement into hot and somewhat 'plastic' (ductile) country rock (cf. Watterson, 1968).

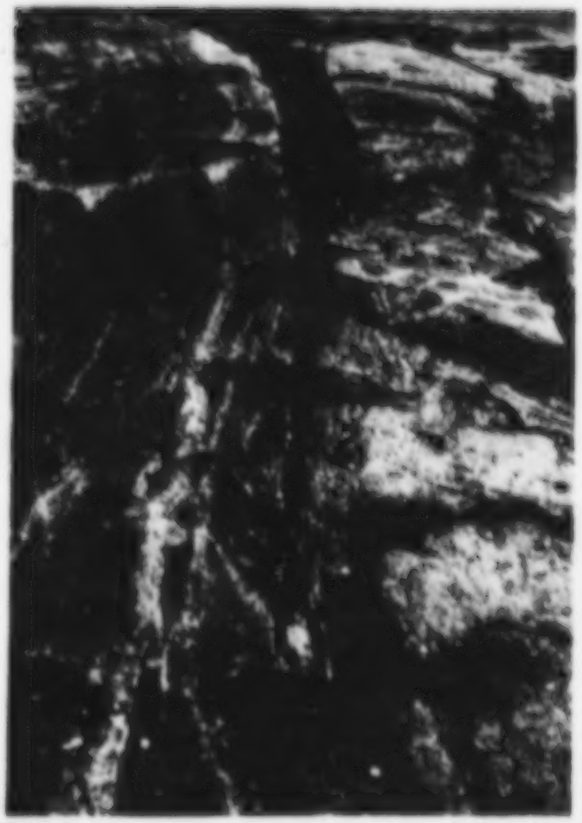

Plate 6. *Cuspate margins on two small metadiabase dykes on Dumbell Island. Note that the left hand dyke has one straight margin, and that the dyke on the right has a very irregular outline that shows both cuspate and horn structure.*

One 030° schistose, plagioclase–porphyritic, dyke on the eastern shore of Web Island is also suggestive of intrusion into ductile and hot country rocks as proposed above. This particular dyke displays one very irregular margin that interfingers with the gneisses and is in places dismembered by felsic veins emanating from the adjacent gneiss. The very irregular margin of the dyke, in consort with dismemberment by (rheomorphic?) veins, point to an apparently mobile condition of the gneisses at time of magma intrusion.

Some of the dykes show the development of narrow apophyses, or horns, where the dyke–country-rock contact is offset. These features are common in basic dykes in any cratonized region, and are thought to be a function of intrusion of magmas into brittle fractures. Currie and Ferguson (1970) have suggested that, in some cases, the formation of such offsets is a direct consequence of fracture-opening caused by the rapid emplacement of a volatile phase directly ahead of the advancing magma. If this concept is applicable to the dykes in the Nain area showing the horned features, then it implies that volatile-influenced fracturing was instrumental in the emplacement of these dykes (see below).

Dyke terminations are of two types—flame-like and bulbous. Flame-like terminations at the end of some dykes are quite spectacular. A continuous 1-m-wide dyke for instance may pass abruptly into a series of parallel, thin, wedge-shaped streamers that penetrate into the gneisses in a closely set group. Other narrower dykes end in wedge-shaped terminations having feathered off-shoots that resemble tuffisite veining (Plate 7). Both these features imply brittle fracture, again perhaps under the influence of high volatile pressures.

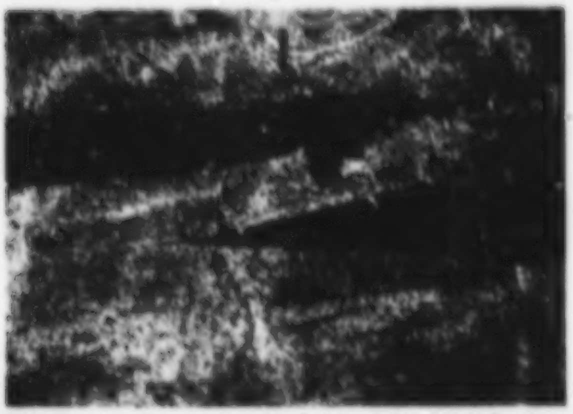

Plate 7. *An offset dyke on Misfit Island showing indications of emplacement into brittle fractures. Note the step-like and 'horned' contacts of the upper dyke and the fine 'feathered' termination of the lower one. The fine felsic veinlets that crosscut and follow the dykes seem to emanate from the country rock.*

One discontinuous amphibolite dyke in schlieric granite on the west shore of Misfit Island locally ends as a blunt, somewhat bulbous body having several sinuous flames. The termination has narrow veinlets of granitoid subparallel to dyke trend that do not appear to be rheomorphic phenomena. This particular dyke, plus a couple of others in the general area, may in fact have been synkinematic and coeval with the emplacement of the host granitoid and may be very early dykes in comparison with the discrete discordant ones. These synplutonic(?) dykes are crosscut by later metadiabase (amphibolite) dykes trending roughly east-west.

Although the majority of the metadiabase dykes are strike-continuous, some show a pinch-and-swell and irregular podiform morphology (Plate 8), while others terminate abruptly, then appear to 'jump' laterally and continue along strike. The pinch-and-swell and podiform dykes are locally similar to basic intrusions described from West Greenland by Nash (1979), and may represent different horizontal sections through vertical fingered sheet intrusions (cf. Pollard *et al.*, 1975). In the Greenland examples, the shape of the dykes is considered by Nash (1979) to be a result of magma emplacement into an active shear zone. There is no consistent correlation between shear zones and podiform dykes in the Nain area, so again the irregular nature of the dykes must largely be a function of igneous emplacement processes rather than a tectonic (deformational) control (cf. Currie and Ferguson, 1970).

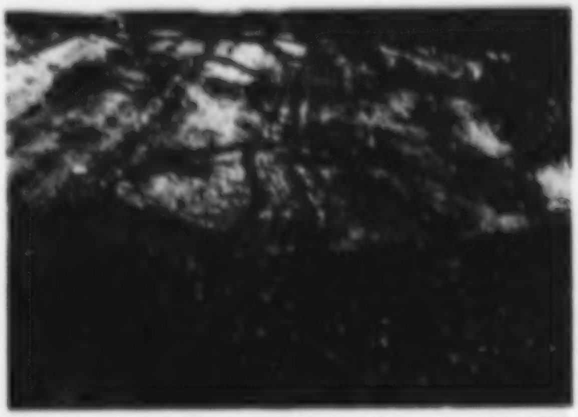

Plate 8. *An undulating metadiabase dyke on northern Web Island. The folding here is considered to be post-emplacement, but may be, in part, syn-intrusive. Note that on the right-hand side of photo the dyke continues along strike as a podiform intrusion with very irregular margins.*

Foliation and Recrystallization

Few of the dykes on the outer islands appear to have escaped recrystallization, and many display well-developed foliations and lineations even when not folded. Recrystallization has occurred under both amphibolite- and granulite-facies conditions but little can be concluded about the distribution and significance of these two different types of dykes at this stage. However, it might be of importance that at one locality on Fermoy Island a foliated 160° granulite-facies dyke is crosscut by a 090°-trending amphibolite dyke that still maintains primary textures. This is not to imply that all 090°-trending dykes are amphibolite; many are plainly at granulite facies (e.g., Carey Island, Misfit Island, Skull Island). In fact, one of the intriguing problems in this area is an explanation for the variable metamorphic character of the dykes. There seems little doubt that intrusion of adjacent plutons has contributed to the metamorphism, but the full effect of this is yet to be determined.

Dykes at both granulite and amphibolite facies occur throughout the gneiss complex, from Lopear Island in the north to the Sungilik Island area in the south. There is no relationship between trend and degree of metamorphism nor trend and style of deformation (foliation development, folding). Some dykes are folded with well-developed axial-planar foliation, whereas others, although not folded, have a margin-parallel fabric or an internally sigmoidal fabric oblique to dyke trend. Generally, these fabrics are not aligned with fabrics in the surrounding gneisses; the dyke fabrics do, themselves, however, show trend variations in some areas (see below). Some granulite-facies dykes are equigranular and lack obvious foliation, and could perhaps be primary noritic dykes; the lack of igneous texture is, however, inconsistent with primary magmatic crystallization. Orthopyroxene-bearing, streaky, discontinuous, 'sweats' are locally developed in some dykes, and these are parallel to the dyke fabric.

Foliations vary from a barely discernable mineral alignment to a pervasive penetrative foliation that locally gives rise to a fissile parting in the dyke. The foliations are not consistently oriented across the area. For instance, on Sandy and Fermoy islands the dyke fabrics trend roughly north-south regardless of dyke orientation and the foliation has S-symmetry. On Carey and Dog islands on the other hand, the majority of the foliations trend between 090 and 140° and have Z-symmetry. These variations in symmetry of foliation relative to dyke margin are suggestive of their development via a conjugate shear couple. However, it is not uncommon to encounter a wide array of dyke and foliation trends in any one area; e.g., on Misfit Island where 020-, 160- and 090°-trending dykes all have internal foliations comparable to dyke trend.

Some dykes appear to have been emplaced, perhaps synkinematically, into shear zones in the gneisses or have been affected by subsequent shearing. These shear zones are either discrete discordant zones into which an external gneissic foliation is reoriented or they are mylonitic high-strain zones (laminated gneisses) that follow the regional gneissic trend in a particular area. In these zones, the dykes are parallel to the trend of the shear and are likewise foliated. Examples of these relationships have been observed on Dumbell Island, south of Ford Harbour and on the large island east of Nukasusutok Island. These types of situations are not common however; more normally, the dykes cut sharply across the regional gneissic layering, which does not show significant deflection or displacement across them, even though the dykes have sigmoidal foliations. The development of sigmoidal, shear-zone type-foliations in discordant dykes, without any indications of shearing and parallel fabric development in the bounding gneisses, indicate that the dykes themselves acted as the loci of shear. The shear regime may even have been contemporaneous with the intrusion and crystallization of the dykes.

NAIN PLUTONIC SUITE

MASSIVE AND FOLIATED ROCKS ON THE ISLANDS

Previous Work

The plutonic rocks around Nain have traditionally been referred to as the 'anorthosite–adamellite suite' (cf. Wheeler, 1942, 1960). However, this duality is somewhat of a misnomer, given the diversity of compositions displayed by these intrusions, and the term Nain Plutonic Suite has been adopted as the formal stratigraphic name (Williams *et al.*, 1985). Four major subdivisions of the plutonic rocks of the NPS are recognized: norite–anorthosite, troctolite, ferrodiorite, and quartz monzonite–granite. For details regarding the general character of the NPS the reader is referred to Emslie *et al.* (1972), Taylor (1979), Emslie (1980) and the various NAP reports cited earlier. The regional distribution of each of the major subdivisions is shown on a recently published colour compilation of the Nain–Nutak area (Ryan, 1990a; *this volume*).

Nain Plutonic Suite in the 1990 Field Area

The NPS was not systematically examined during the 1990 survey. Only where the igneous rocks abut the gneisses were they examined on the outer islands and these few occurrences are dealt with below. Elsewhere where the NPS was encountered, the rocks are strongly deformed and recrystallized; these are dealt with in a subsequent section.

Medium- to very coarse-grained, dark grey norite cut by grey to white granite dykes forms the islets between Fermoy and Carey islands (Figure 3). A similar, although overall finer grained, rock occurs on the eastern point of Carey Island, where it contains rafts of pale grey leuconorite. These rocks are all considered to be part of the Jonathan intrusion (Berg and Briegel, 1983), a large layered intrusion that underlies several of the islands directly north of the study area. Grey-weathering leuconorite and anorthosite on the northern shore of Dog Island and adjacent smaller islands may be part of the same intrusion.

Dark grey to black norite, similar to that on eastern Carey Island, also underlies Club Island and the adjacent shore of Central Island (Figure 3). The norite here is plainly polyphase, with finer grained dykes disrupting a coarser grained variety, and the whole is cut by white granite dykes. Pale grey leuconorite underlies Pat Rocks and outcrops on the western part of Noazunaluk Island and Noazunakuluk Island. These rocks are part of an extensive noritic composite pluton that constitutes the nearby Hillsbury Island and Paul Island, and forms the western part of West Red Island (cf. Wiebe, 1990). On Noazunakuluk Island, the easternmost part of this unit is a foliated, recrystallized, sugary, biotite-bearing anorthosite, in which the fabric is parallel to that in nearby mafic granulite. The distribution of the foliated anorthosite was not investigated, but it does not appear to be as extensive as in some other areas examined during the 1990 season (see below).

Noritic and leuconoritic rocks were also observed on outer Whale Island, Baker Island, Jenks Island, parts of Skull Island, and the outer third of Sandy Island.

A group of iron-rich, fine- to medium-grained gabbronoritic rocks locally forms a distinctive, chocolate-brown-weathering assemblage within the NPS, usually separating anorthositic and granitic plutons. Within individual intrusions there is a range of compositions from gabbroic through to granodioritic with the former being most common. De Waard (1974a) proposed that these rocks be termed monzogabbro, a name that he felt reflected the median composition and stressed the abundance of pyroxene and scarcity of amphibole, or monzodiorite, reflecting the presence of andesine feldspar. R.F. Emslie (personal communication, 1990) refers to these rocks collectively as ferrodiorite, a name originally coined by Wager and Brown (1967) to refer to similar rocks in the Skaergaard intrusion of Greenland, in which the plagioclase feldspar is less calcic than An_{50} and the ferromagnesian minerals are iron-rich.

The ferrodioritic rocks outcrop on Dog Island (de Waard, 1974b) where they were examined in detail during the 1990 field season by R.F. Emslie of the Geological Survey of Canada. This same suite of rocks seems to continue southward through Skull Island and nearby islets to the south (Wheeler, manuscript maps) and also crops out along the south shore of Sandy Island (Figure 3). All these occurrences are characterized by spectacular examples of magma mingling in which gabbroic magma has interacted with a partially crystallized granitic magma. This has produced field features that range from simple intrusive relationships to total mixtures in which a mafic to intermediate host contains abundant ovoids of feldspar and quartz derived from the granite. At 'Camp Bay' on Dog Island, the northernmost contact of the ferrodiorite against the gneisses is characterized by a very strong, steeply dipping foliation. This is apparently not an uncommon feature in this area, for de Waard (1974b) describes the presence of 'flow structure' (interpreted by the writer to mean foliation) from this body elsewhere on Dog Island. More homogeneous ferrodiorite occurs on West Red Island (cf. Wiebe, 1981), here it is well layered and varies compositionally from diorite to pyroxenite with little indication of contamination by granitic magma. A weak foliation was noted in this rock at one locality visited, which, according to Wiebe's (1981) descriptions, is not the only deformational feature of this body. However, none of the deformational features seen by this writer in the ferrodioritic rocks described here are as intense or pervasive as in the plutonic rocks to be described in the following section.

The granitic rocks of the outer islands were examined on Carey, Dog and Whale islands and several other small islands between. In all cases, the rocks are hornblende-rich, with local indications that they may also contain olivine and pyroxene(s). The Dog Island granites have previously been investigated by de Waard (1973) who named the body north of 'Camp Bay' the 'Alagaiai adamellite' and that south of the bay the 'Iviksuak adamellite'. The southern body was examined in only a few outcrops, where it is a white to yellowish brown weathering, hypidiomorphic, hornblende granite that locally contains ovoidal feldspar and quartz. De Waard (1973) interpreted this granite as being in transitional contact with the nearby anorthosite via a 'granodioritic porphyry' (i.e., ferrodiorite).

The 'Alagaiai adamellite', where examined by the writer, is disposed in a series of east–west-trending hornblende–granodioritic dykes. The granodiorite exposed on Red Rocks and Carey Island is also interpreted to be part of the same dyke network (Figure 3). Rusty cores in hornblende and a greasy green colour to some fresh samples suggest the presence of fayalite.

Hornblende granite of the same type as above also outcrops on the Karl Oom Islands and through central Whale Island. The eastern contact between granite and gneiss on Whale Island is one in which granite sheets and gneissic screens alternate on the scale of a few metres to hundreds of metres.

Grey, hornblende- and biotite-bearing tonalitic dykes are not uncommon in parts of the gneiss complex. These are all late intrusions relative to other components in the gneiss complex, including the metadiabase dykes, but may themselves be of more than one age. They are fine- to medium-grained rocks, locally with internal compositional variations producing a polyphase assemblage, and usually occurring as 1- to 3-m-thick dykes. Dyke attitude varies from vertical to subhorizontal. Several dykes of this type display a well-defined lineation defined by a streaky alignment of mafic constituents.

Biotite-bearing, coarse-grained to pegmatoidal, pink, granite dykes are common on the two large islands directly east of Nukasusutok.

FOLIATED, RECRYSTALLIZED AND GNEISSIC ROCKS WEST AND NORTH OF NAIN

Some Early Descriptions of Foliated Plutonic Rocks

One of the most surprising facets of the 1990 season was the recognition of areally extensive zones of deformed and recrystallized noritic and anorthositic rocks in the Nain region. However, not only are there deformed basic rocks, but a brief examination of the Anaktalik Brook area indicates the presence of younger rusty-brown granitoid rocks in association with the basic rocks that are likewise deformed. A perusal of the existing literature, especially the Nain Anorthosite Project reports (Morse, 1971-1983) pertaining to the areas where deformed basic rocks have been observed by the writer indicates that some of the deformed rocks have previously been recognized, and, in some cases have been mapped as discrete geological units, but their origin was not always addressed. Wheeler's manuscript maps show many of the foliated noritic rocks as 'granulite of uncertain origin' and some NAP reports refer to 'stretched anorthosite' and 'foliated anorthosite'. In some cases, deformed rocks of the type described here seem to be designated as having a 'mineral lamination' or 'flow structure'. In all cases, the foliations in these rocks have been ascribed to pre-consolidation deformation. However, it seems that the extent of the deformation and recrystallization of the plutonic rocks has not been appreciated. Morse (1983a, p. 12,13) proposed that the 'stretched anorthosite' reflected an early anorthosite event in the overall emplacement history of the NPS, but acknowledged that the deformation exhibited by such rocks was problematic, probably not all of the same age, and could conceivably postdate consolidation.

From his earliest work on the rocks of the Nain area, E.P. Wheeler recognized that parts of the anorthositic terrane were texturally anomalous. For instance, in his 1942 paper he described (i) dark plagioclase crystals transected by white plagioclase veins, (ii) larger dark plagioclase crystals set in an equant fine-grained, white plagioclase matrix, (iii) warped cleavage planes in plagioclase and orthopyroxene, and (iv) the development of mortar structure. He also noted that hypersthene may form 'fluidal tongues' and that many of the larger grains exhibited a 'polysomatic' texture. He suggested at one point in this paper (p. 617) that the original subophitic texture of these 'non-diabasic' anorthositic rocks was destroyed by stress to produce the above features, but in a later part of the same paper maintained that the anorthositic rocks 'have not been subjected to any great degree of dynamic stress since their consolidation' thus implying that the destruction of the primary igneous textures must have occurred in the magmatic environment by 'differential flow during the late stages of consolidation' (cf. Wheeler, 1955, p. 1054). Wheeler (1960, p. 1761) noted that 'the available data give the impression that foliation in the anorthosite complex is best developed near margins'. He was also conscious of the unique character of the anorthosites in which white plagioclase was dominant—he erected a 'pale facies' to denote their marble-like paleness, and observed that within a regional context these rocks were most widely developed in the central part of the Nain 'complex' (Wheeler, 1960).

Wheeler (1960) initially believed that the development of foliation within the granitoid rocks was 'rare, if not absent', but he later (Wheeler, 1969) described 'adamellite' of the Nain Bay area having a penetrative fabric parallel to the margins of the intrusions. However, his manuscript maps indicate that in places, such fabrics are in fact quite discordant to pluton contacts. He attributed these foliations to primary igneous flow processes, namely, that they developed while the magma was being emplaced as crystal mush along a contact between gneiss and foliated anorthosite; the foliation was deemed to be a function of movements resulting from tectonic pulses during consolidation of the adamellite magma (see also Emslie *et al.*, 1972, p. 55).

Observations on Foliated Plutonic Rocks during the 1990 Season

A brief examination of anorthositic rocks adjacent to Tasiuyak gneiss northwest of Kingurutik Lake (Figure 2) was undertaken while conducting helicopter reconnaissance of the latter rocks (a septa of the Churchill Province rocks within the interior of the NPS). Contact metamorphosed Tasiuyak gneiss and associated charnockitic to gabbronoritic granulite is separated from 'pale facies' recrystallized anorthosite by a 300- to 400-m-wide zone of strongly foliated and recrystallized norite and noritic gneiss. Wheeler's manuscript maps for this area show these rocks as 'granulite of uncertain origin', but in a field guide by Emslie *et al.* (1972, p. 44), he noted the pale anorthosite and paragneiss of this region are separated by a zone of norite in which 'foliation becomes continuous and pronounced, and the texture becomes more gneissic'. He described a specimen from this zone as an 'apatite—ilmenite—orthopyroxene dioritic gneiss with anorthositic affinity'. Brand (1975, 1976), working in an area slightly south of that examined by the writer described a 'marginal anorthosite' displaying a 'foliation ..... of mafic minerals' and 'pyroxene lineation'; this writer interprets the 'marginal anorthosite' to be correlative with the foliated norite seen directly to the north. This indicates that in the Kingurutik area the zone of foliated and gneissic norite separating relatively pure (yet recrystallized) anorthosite from the surrounding gneisses is at least 20 km in length. Similarly, using Wheeler's distribution of 'pale facies' anorthosite as shown on his manuscript maps and in Wheeler (1969, p. 190, 191), implies that recrystallized anorthosite underlies a vast area in the Kingurutik River region. (It is interesting to note that Brand (1976) failed to recognize the contact metamorphic effects from plutonic rocks in this region; in fact, his descriptions of cordierite, hypersthene and spinel habits within the Tasiuyak gneiss indicate that these minerals are plainly a result of the replacement of garnet and sillimanite; cf. Ryan and Lee, 1986).

Wheeler's manuscript maps portray a zone of 'granulite of uncertain origin' bordering 'pale facies' anorthosite to the west and north of Webb Bay. This 'granulite' zone, too, is strongly deformed and recrystallized norite (Plate 9), noritic gneiss and anorthosite, which at outcrop scale forms a well-layered gneissic complex akin to nearby Archean quartzofeldspathic granulite, but without a migmatitic neosome. A brief examination of several outcrops on the western side of the bay (Figure 2) revealed that the foliated rocks are transected by post-deformational granitic dykes in which the feldspars are largely recrystallized to sugary polygonal aggregates as in the rocks they cut. The 'pale-facies' anorthosite to the west of the gneissic noritic rocks is likewise recrystallized, comprising grey plagioclase relicts in an otherwise white groundmass. The polygonal monomineralic nature of the recrystallized anorthosite rocks masks deformational fabrics if present; however, orthopyroxene in zones of 'clotted fabric' (cf. Wheeler, 1960, Figure 3) are plainly deformed, and the larger orthopyroxene megacrysts (locally with visible exsolved plagioclase lamellae) are tailed-out, their margins are recrystallized to polygonal aggregates, and their massive interiors have warped cleavage faces.

A brief reconnaissance of the near-coastal area south of Webb Bay indicates that this assemblage of rocks continues towards Nain. Certainly, Mount Lister (Figure 2) is composed of variably recrystallized anorthosite; basic (ferrodioritic?) dykes, prominent features in the steep cliff faces on the eastern flank of the mountain, are diffusely banded and foliated parallel to their trend. Similarly, white foliated anorthosite and more melanocratic noritic rocks also occur east of Conch Bay and on the islet west of Barth Island, where they have been previously included as part of the Archean basement (Rubins, 1971) or else 'granulite of uncertain origin' (Wheeler, manuscript maps). Recrystallized, but non-foliated, noritic rocks have been observed on the shoreline of Sachem Bay

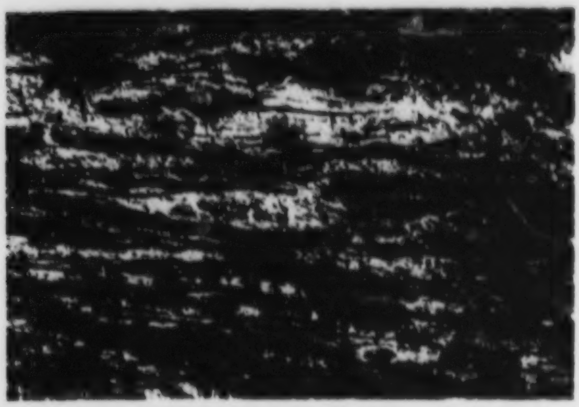

Plate 9. *Strongly foliated norite, Webb Bay. Black lozenges and streaks are orthopyroxene. Light grey areas are recrystallized plagioclase in which remnants of original larger grains are preserved (darker grey areas).*

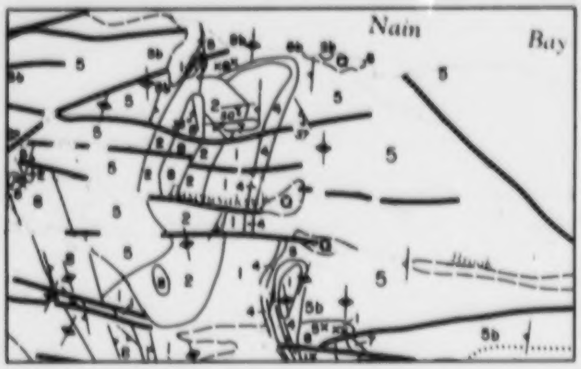

Figure 4. *Area directly south of Nain Bay examined during helicopter reconnaissance (see Figure 2) showing rock units according to E.P. Wheeler's manuscript maps (from A. Harris, 1980). See text for relevant unit descriptions and discussion of 1990 reconnaissance survey of this area.*

(Figure 2), close to banded noritic 'granulite' that may be equivalent to rocks on Carey Island and at Higher Bight described earlier. Rubins (1971) has mapped 'foliated anorthosite' and various basic granulites west of Nain village and north of Barth Island that are probably a continuation of the Webb Bay assemblage. A brief examination of one of Rubins' outcrops of 'foliated anorthosite' on the coast west of Nain indicates that it is a strongly foliated norite, with tailed-out pyroxenes and lozenges of grey plagioclase, a rock that is easily correlatable with the noritic gneisses west of Webb Bay. However, the Nain outcrop examined has deformed basic dykes subparallel to the foliation, and the foliated norite is, in one part of the outcrop, crosscut by a small dyke network of undeformed, subophitic-textured norite. Rubins (1971) failed to recognize that 'pale facies' anorthosite west of his foliated anorthosite is likewise a recrystallized rock in which, like at Webb Bay, a deformational fabric is visible only where orthopyroxene is present. Many basic dykes, visible in coastal cliffs of the white anorthosite, were not examined, but are quite likely similar to those on the east flank of Mount Lister.

At the end of the 1990 field season, a brief helicopter reconnaissance excursion was undertaken between Anaktalik Brook and Nain Bay (Figure 2), in areas shown on Wheeler's manuscript maps to be underlain by his Units 1 and 2 (Figure 4). Based on this writer's previous experience using the above maps, Wheeler's Unit 1 corresponds to Nain Province Archean gneisses, and his Unit 2 corresponds to Proterozoic Tasiuyak gneiss of the Churchill Province; the goal of the excursion was to define the nature of the Nain–Churchill boundary in this area. This area proved to be much more complex than is apparent from Wheeler's work, an inkling of which can be gleaned from the observations to follow.

For instance, three outcrops of his Unit 1 were visited. Two of these are granulite-facies quartzofeldspathic gneiss containing concordant mafic units derived from mafic dykes; the other outcrop is deformed anorthosite. This anorthosite is identical to rocks just south of Anaktalik Brook previously considered to be Archean anorthosite by Ryan and Lee (1986); however, based on the similarity between these rocks and the foliated anorthositic rocks from the Webb Bay–Nain area above, a re-evaluation of this earlier interpretation may be in order. (One can, of course, always entertain the possibility that all deformed noritic and anorthositic rocks are in fact Archean, and akin to similar rocks elsewhere in Labrador and Greenland.) 'Granulite of uncertain origin', designated by Wheeler as Unit 4, and shown to occur as a narrow zone in this area (Figure 4), is foliated and recrystallized norite like that of the Kingurutik River–Webb Bay–Nain area.

Wheeler's Unit 2 gneiss in this area is not Tasiuyak gneiss. In fact, his Unit 2 is quite variable. Predominant is a orange-brown-weathering rock that is a simply foliated and well-lineated megacrystic granitoid. Without its penetrative fabrics it is identical to some of the massive rapakivi-like granitoid rocks that are an integral part of the NPS. Wheeler, in fact, recognized this, and shows it on his manuscript maps as Unit 8 (his 'adamellite'), where there is no foliation present (Figure 4). There is no obvious compositional difference between his Units 2 and 8, and they are considered by this writer to be the same unit, exhibiting inhomogeneous foliation and lineation development. However, within this area, there are rocks that are certainly part of the Churchill Province. These are brownish-yellow enderbitic and gabbronoritic gneisses akin to those elsewhere in eastern Churchill Province.

Wheeler's 'pale facies' anorthosite (Unit 5, 5b, Figure 4) in the Anaktalik Bay–Nain Bay area is, where examined at least, recrystallized, albeit to varying degrees. Outcrops examined directly west of the foliated 'rapakivi granites' are all foliated and pervasively recrystallized white-weathering rocks, in places cut by rapakivi granite and brown ferrodioritic dykes that are also foliated and lineated; similar anorthosite and 'foliated orthopyroxene meladiorite dykes' have been described by Wheeler (1969) at Tessersoakh Lake, 10 km northwest of the area examined by this writer. Recrystallized anorthosite also occurs around the Pearly Gates, a small area between Anaktalik Brook and Nain Bay named for its iridescent labradorite, which, in places occurs in crystals up to a metre across. Recrystallization here, however, is limited to small irregular zones in which the otherwise dark-grey feldspar is replaced by a chalky-white equigranular aggregate. Common to the more massive grey anorthosite is a conspicuous, narrow white fracture pattern to the plagioclase; along some of the larger fractures the grey feldspar has polygonized to white sugary aggregates. These features correspond to Wheeler's descriptions of some of the anomalous characteristics of the 'non-diabasic' anorthosites noted earlier.

Wheeler's manuscript maps show several elongate bodies of 'adamellite' in the Anaktalik Brook–Nain Bay area (Unit 8, Figure 4). One of these was examined in one outcrop area only. At the locality visited, the rock is a slightly rusty-weathering monzonite, in which streaks of pyroxene (+ hornblende?) locally define a well-developed foliation. On fresh surface, the rock has the greenish hue common to olivine-bearing assemblages of the NPS; fayalite indeed occurs in a sample of this rock collected for geochronological studies by R.F. Emslie (personal communication, 1990). At the locality visited, the monzonite also contains rafts of white, recrystallized anorthosite that are common in this whole region.

An interpretation of E.P. Wheeler's manuscript maps, together with this writer's observations, prompts the predictions that 1) much, if not all, of Wheeler's 'pale facies anorthosite' inland between Anaktalik Brook and Okak Bay (cf. Wheeler, 1969) is, in fact, variably deformed and recrystallized rock, 2) much of his 'granulite of uncertain origin' in the same area consists of foliated and recrystallized norite, and 3) many of the 'adamellites' of this region (which have foliation symbols on his manuscript maps, Unit 8, Figure 4) are correlatives of the deformed monzonite and granite described above. Indeed, in the guidebook paper by Emslie *et al.* (1972, p. 55, 56), Wheeler provided good descriptions of such foliated adamellitic rocks on the north and south shores of Tessersoakh Lake, attributing the development of the fabrics to primary magmatic flow. Into this category of deformed and recrystallized rocks, this author would also include the Bird Lake Massif and Suzie Brook slab (Morse, 1983b), as well as foliated anorthosite described by Berg (1974) in the vicinity of Port Manvers Run. The North Ridge Gabbro (Berg, 1973), a foliated and lineated rock west of the Hettasch Lake layered intrusion, and the Bridges layered intrusion (Planansky, 1971) are probably also members of this group of rocks. The Bridges intrusion exhibits igneous layering, but its constituent minerals are strongly polygonized and recrystallized (R. Wiebe, personal communication, 1989). If future work confirms these predictions, it is obvious that the areal distribution of the foliated and recrystallized rocks is enormous. This has implications for emplacement mechanisms of the Nain Plutonic Suite.

AREAS OF DEFORMED/RECRYSTALLIZED PLUTONIC ROCKS OUTSIDE THE MAIN NPS

Outside the areas mentioned above, all of which on the basis of present knowledge must be considered to be part of the NPS, there are other areas discovered during the 1990 season where deformed and recrystallized plutonic rocks akin to those of the NPS occur. These are on Georges Island at the entrance to Webb Bay, at Challenger Cove, and on Satok Island (Figure 2).

The northern shore of Georges Island (the only part of the island examined) and an adjacent small island to the north comprise a black-weathering (olivine-bearing?) norite. This rock is thoroughly recrystallized (plagioclase is white and saccharoidal, pyroxene is altered to amphibole) and it is crosscut (on the small island) by two foliated and lineated metabasic dykes (now amphibolites). Across the bay mouth, at Challenger Cove, an identical rock occurs on the north shore, here transected by shear zones in which the rock is converted to a streaky amphibolite. On the southeast shore of the cove, the norite is characterized by a finer grain-size, and the presence of a 'clotted fabric'. Here, too, shear zones are developed, producing amphibolite from the original noritic rocks. The Challenger Cove rocks have been previously referred to as 'granulite of uncertain origin' by Wheeler (manuscript maps), and as 'gneisses of uncertain origin' by Woodward (1973).

The eastern half of Satok Island is composed of a variety of deformed and/or recrystallized plutonic rocks (Figure 3), which on existing maps (cf. Wheeler, manuscript maps; Taylor, 1979) are assigned an Archean age. However, this age designation is open to re-interpretation. Directly adjacent to the granulite-facies gneisses that form the western half of the island is a unit of foliated oxide-rich rock resembling some of the ferrodioritic members of the NPS. This is succeeded eastward by a narrow monzonitic zone, then a second gneissose mafic unit, and then an extensive pale-brown-coloured monzonitic zone containing rafts of white, recrystallized norite. The monzonite and its inclusions are cut by amphibolite dykes at one locality; in a nearby locality, a phlogopite–pyroxene–carbonate dyke is present, interpreted as a probable metamorphosed alkaline rock. The northeastern part of the island appears to comprise largely chocolate brown, oxide-rich ferrodiorite or rapakivi granite–syenite, whereas the eastern coast of the island is a fairly massive to slightly foliated white-weathering meta-anorthosite. A brief examination of the islets just south of Satok indicates these are largely black, (olivine-bearing?) recrystallized norite, like that on Georges Island. The full extent of this plutonic assemblage is not known.

LARGE DYKES OF NORITIC TO TROCTOLITIC COMPOSITION

The rocks included in this category include several prominent intrusions on northern Dog Island, a north-trending dyke on Dumbell Island, several dykes on Carey Island and a dyke on the long island east of Sungilik Island.

The Archean basement on the northern half of Dog Island (Figure 5) is intruded by several east–west- to southeast–northwest-trending dykes that appear on field examination to be olivine-bearing noritic to gabbroic rocks. These are older than the Dog Island granite, but their relationship to the other Middle Proterozoic rocks here is unknown. With the exception of the second east–west dyke north of 'Camp Bay', which is black, these are brownish-grey-weathering, equigranular rocks. Locally, the plagioclase appears to be recrystallized, and the dyke margins may be sheared. One such dyke is characterized by an igneous layering whose attitude is normal to the dyke trend; the layering is folded into moderate folds, which have a well-developed axial-planar foliation.

Northwest-trending dykes like those above also occur on Carey Island. At least one of these, a 15-m-wide dyke which has layering oblique to margins, crosscuts well-layered 'mafic granulite' that may be a marginal phase of the norite to the east. A larger dyke, that appears from aerial reconnaissance to extend northward across the island, is a recrystallized olivine-bearing noritic rock. It has a near-margin internal zone with a spongy, discontinuous type of layering, and a strongly foliated and lineated amphibolitized margin.

A massive, undeformed 8-m-wide brown-grey olivine gabbro forms a north-trending dyke on Dumbell Island and on the small island east of Misfit Island. This dyke shows no indication of a penetrative fabric, and it exhibits chilled margins against the Archean gneisses. This dyke may be related to the younger gabbro dykes described in the next section.

One short traverse across a long island east of Sungilik Island suggests that the east-trending central spine of this island is a large recrystallized olivine norite or ferrodiorite dyke. In places, it is characterized by porphyritic and mingled textures akin to the ferrodiorites on Dog Island and Skull Island, and is intruded by the pink aplite that underlies most of the north shore of the island. An outcrop on the central coast of the north shore comprises foliated brownish-weathering rocks resembling the dyke having folded layering on northern Dog Island. A rock of similar composition appears to form part of the western shore of Nuasurnak Island. Further work is necessary in this area to fully define the nature of these rocks and their relationships to the surrounding gneisses and other plutonic rocks.

FRESH DIABASE AND GABBRO DYKES

Dense, black to brownish-weathering, fresh diabase dykes were noted for instance on Noazunakuluk Island, Pat Rocks, on the northeast coast of East Red Island, on the northern tip of Whale Island, on the north shore of Higher Bright, on the large island east of Nukasusutok Island, and at Ford Harbour. These are all fine- to medium-grained rocks, rarely exhibiting black plagioclase megacrysts. Chilled margins are conspicuous on some dykes, and some are vesicular. The most spectacular example of a fresh dyke is a 60-m-thick coarse-grained gabbro that forms a prominent black band across the western half of Skull Island; Wheeler's manuscript maps show this dyke extending eastward across the whole island.

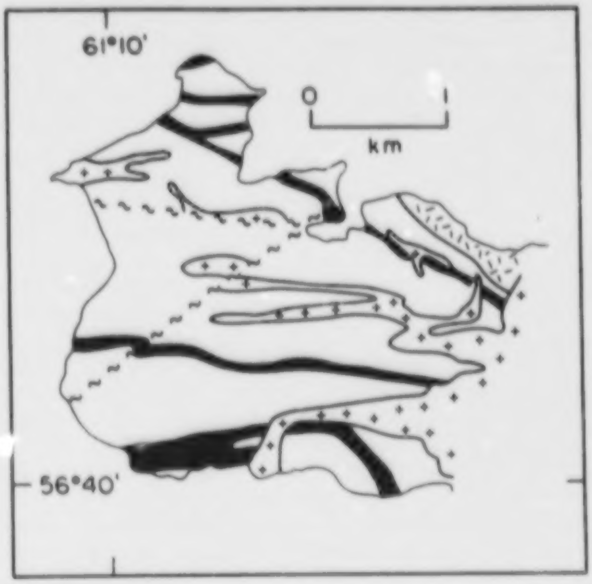

Figure 5. *Sketch map of northern part of Dog Island showing distribution of thick olivine-bearing basic dykes (black). The second dyke to the north may be part of the older (metadiabase) dyke swarm. The Archean gneisses are unornamented, norite is shown with random dashes, and granite is designated by crosses.*

Most of the fresh dykes trend within a few degrees of east-west, and since these intrusions occur within the basic plutons as well as within the gneisses, all such rocks are assumed to be post-anorthosite. None of the posttectonic granitoid rocks examined by the writer are cut by dykes but quite likely these dykes postdate the felsic plutons as well. Absolute ages may range as young as Tertiary as suggested by Bridgwater *et al.* (1990). Based on descriptions given by Wiebe (1985) they are probably correlative with his low-phosphorus series and illustrate the further extent of dykes that are considered to be broadly equivalent to the Harp dykes (Meyers and Emslie, 1977).

METAMORPHISM AND STRUCTURE

The islands surveyed during 1990 expose gneissic rocks that are part of a north-south septum between two plutonic masses of the NPS (Figure 1). It has been already well established that thermal effects from the NPS were responsible for contact metamorphic transformations in the regional assemblages of the gneissic rocks into which the plutons were emplaced (cf. Berg, 1977a; Lee, 1987). One of the most diagnostic mineralogical changes, and one that is easily recognized in the field, occurs in paragneisses that are adjacent to the intrusions. In rocks at pyroxene hornfels facies, garnet is replaced by hypersthene and cordierite, and sillimanite is replaced by cordierite and spinel. Since these transformations are apparent in the paragneiss units throughout the islands surveyed this year, it is not unreasonable to conclude that the imprint of pyroxene-hornfels-facies contact metamorphism has blanketed all of the gneissic country rocks. The fact that garnet and sillimanite pseudomorphs still retain their pre-replacement shapes (ovoidal and streaky, respectively) shows that the gneisses were not subjected to deformation during this metamorphism.

Dykes similarly show assemblages that conform to pyroxene hornfels (granulite) facies, but as has been noted previously, the metamorphism of the dykes appears to be a complex affair, and must await petrographic study before definite conclusions can be advanced. It may be, for example, that the dykes all predate the NPS and the assemblages of the amphibolite dykes represent varying degrees of retrogression from a 'regional contact' metamorphism of pyroxene hornfels (granulite) facies or else reflect greater distance from the pluton. On the other hand, the granulite-facies dykes may predate the NPS while the amphibolite-facies dykes may represent intrusions into the gneisses as the thermal effects from the NPS were waning.

Although the gneisses and their dykes have been subjected to a pyroxene-hornfels thermal metamorphism, it is also evident that the gneisses had reached granulite facies prior to dyke intrusion. This is based on observations that basic dykes plainly transect rocks with orthopyroxene-bearing 'sweats' that had formed before dyke emplacement. If the dykes that cut such melts are Early Proterozoic in age, then this high-grade metamorphism is quite probably Archean. If, on the other hand, the dykes are Middle Proterozoic, then this metamorphism may have been Hudsonian, or even related to events accompanying emplacement of early NPS plutons, which are also cut by such dykes.

Amphibolite-facies gneisses in the area show indications of having been at granulite facies, and blebby retrogressed granulites are locally a distinctive member of the quartzofeldspathic rocks. To date, there is insufficient data to compare metamorphic assemblages in the gneisses with those in the dykes that cut them, so the relative timing of the retrogression is unknown.

De Waard (1971) pointed out that the deformational history of the gneisses on Paul Island is plainly polyphase, but he felt that the major features were developed as a result of anorthosite intrusion. However, this seems unlikely, for it is obvious from the map pattern that the plutonic rocks on Dog Island clearly cut across earlier interference patterns in the gneisses (Figure 3). In addition, on a mesoscopic scale, mafic dykes crosscut tight folds, open folds, and interference patterns in the gneisses; even if some of the dykes are related to the incoming plutons, this relationship shows that the fundamental features of the gneiss complex were attained prior to this Middle Proterozoic plutonism.

As noted above, interference folds in outcrop and on map-scale indicate a polyphase deformational history. The continuity of structures through the area is somewhat tenuous, mainly because of the scale of mapping. It is obvious that on a regional scale there is considerable variation in trend of the gneissosity (Figure 6). On Dog Island, for instance, the foliation attitudes and distribution of supracrustal gneisses point to map-scale interference fold structures. However, on the islands to the west, the gneisses maintain a more consistent north-northeast trend. Southward toward the Red Islands, the gneissosity swings eastward in an apparently simple manner. It defines fold structures with east-trending axes on East Red Island and Paul Island, but this too is a simplified picture since the mafic units north of Ford Harbour outline earlier structures, and coastal reconnaissance south of Ford Harbour indicates shallowly plunging dome and basin patterns. East of Nukasusutok Island the trend of the gneissosity and distribution of supracrustal units again define north-northeast-trending fold structures.

The gneisses locally display zones of high strain in which the gneissic banding has a mylonitic aspect. The two best-developed zones of this type occur on the south shore of Carey Island and the south shore of the large island east of Nukasusutok Island. On Carey Island, the 'straight gneisses' are gently dipping and have a well-developed lineation; the gentle dip is a function of re-orientation by open, shallowly plunging fold structures. The zone is cut by a massive metadiabase dyke. East of Nukasusutok, a similar straight belt with a moderately S-plunging lineation is steeply dipping, and is in part occupied by a foliated amphibolite dyke. The age of formation and the extent of such zones has not been fully evaluated.

Rarely does there seem to be any direct relationship between mesoscopic structures in the deformed dykes and in the enclosing gneiss. This requires an explanation. The development of foliations and lineations in the dykes, yet not in adjacent gneisses, indicates that at the time of their deformation the basic intrusions were far more susceptible to recrystallization, perhaps an indication that they were hot and therefore, weaker than the host rocks at the time of deformation (cf. Watterson, 1968). It should also be noted that folded dykes tend to be those that were originally oriented nearly normal to the trend of the gneissosity in the country rock; the majority of the highly discordant dykes, however, are not folded.

DISCUSSION

The geological history of the Nain area appears to be much more complicated than can be appreciated from existing information on the area. This section presents some brief comments on possible correlatives of the regional gneiss terrane, but focusses mostly on the problems posed by the basic dyke swarm and by the recognition of the extent of the deformed and recrystallized plutonic rocks within the NPS. With respect to the final points, several fundamental questions are posed.

1. What is the age and origin of the basic dyke swarm in the gneisses?

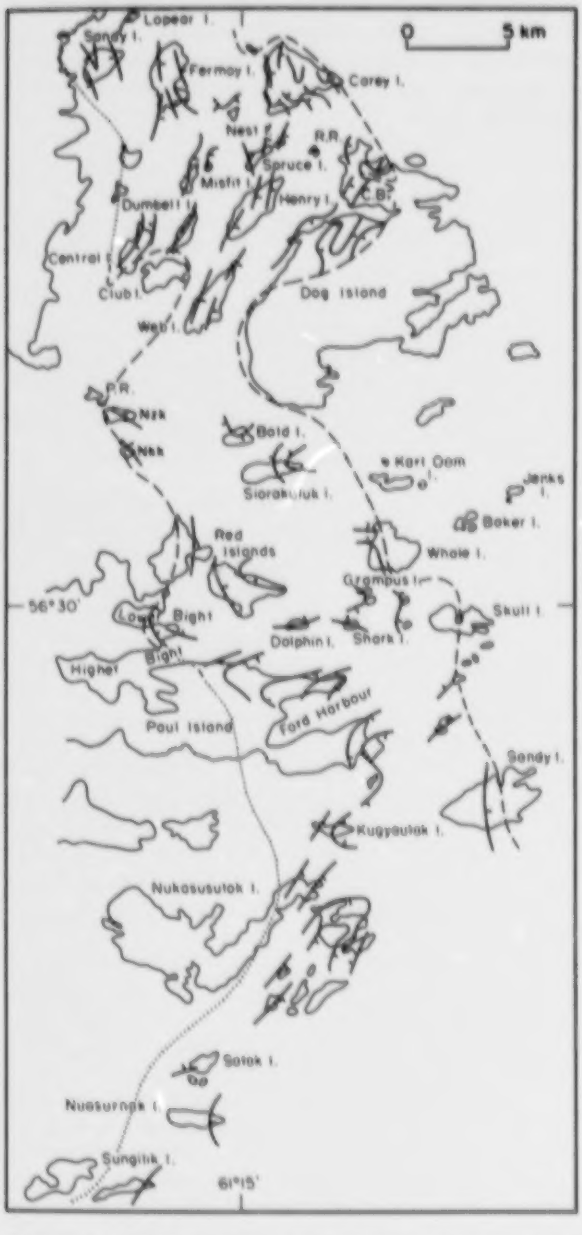

Figure 6. *Generalized trend of regional gneissosity shown as heavy lines with barbs. Broken line is approximate contact between plutonic rocks and gneisses, dotted where compiled from other sources. Note that effects of late strike-slip faults have been ignored for purposes of this sketch. See Figure 3 for key to islands.*

2. Is there more than one discrete episode of basic magmatism?

3. What caused such regionally developed deformation and metamorphism of the dykes? and,

4. Why are there deformed and recrystallized plutonic rocks in an anorogenic igneous suite?

THE REGIONAL GNEISS TERRANE

The Archean quartzofeldspathic–orthogneiss complex is obviously a polygenetic series of rocks, comprising multigeneration migmatite at granulite and amphibolite facies and a variety of more homogeneous granitoid rocks. The layered gneisses have no distinct features to suggest direct correlation with the Early Archean of northern Labrador, but the presence of Saglek-dyke type mafic units at Webb Bay are suggestive of such correlation (see also Bridgwater *et al.*, 1990). The development of orthopyroxene- and garnet-bearing melts is another feature that this area has in common with Late Archean granulite-facies metamorphism in northern Labrador. The multiphase whispy granitoid gneisses that intrude the migmatite grey gneiss in the Henry Island–Dumbell Island area resemble the 3050 to 3000 Ma Nûk gneisses and other polyphase mid-Archean gneisses of West Greenland; large areas of rock directly correlative with these ca. 3000 Ma Archean units of Greenland have yet to be firmly identified by isotopic dating in Labrador, but the Dumbell Island–Misfit Island rocks are good candidates. The presence of apparently syn-plutonic basic dykes in the whispy granitoids of Labrador is also a feature of the Greenlandic mid-Archean gneisses (cf. Chadwick and Coe, 1983).

Supracrustal rocks are not nearly as abundant in the Nain area as they are in the Saglek area, perhaps reflecting an overall greater volume of middle Archean orthogneiss than in the north. The apparent abundance of quartzite around Ford Harbour and on some of the islands is also a characteristic of the supracrustal rocks here that differs from northern Labrador.

THE BASIC DYKE SWARM

The profusion of basic dykes represents one of the most intriguing features of the rocks around Nain, and the following discussion focusses on these. The younger undeformed dykes are not addressed here, since these have been adequately discussed by Wiebe (1985); instead the comments are restricted to the metamorphosed and deformed dykes. Unfortunately, although it is easy to demonstrate several generations of such dykes in many gneissic outcrops around Nain, there is no firm evidence of their absolute age. As pointed out earlier, determinations of relative age between isolated dykes is also a problem, since the data at present do not allow firm correlation between trend and age. Similarly, there does not seem to be any correlation between particular morphological characteristics and dyke trend. In addition, there is no obvious correlation between dyke trend, relative age, the presence or absence of deformation and the degree of metamorphism. All these features make discussion of the significance of the dykes somewhat difficult, so a simple premise is adopted as a foundation for discussion. This premise is that there are potentially at least two discrete episodes of basic magmatism represented by the dyke swarm: (i) an Early Proterozoic one and (ii) a Middle Proterozoic one. In addition, the occurrence of features in some dykes in the whispy granitoid gneiss akin to those seen in synplutonic mafic dykes from felsic igneous terranes suggests these may be approximately the same age as their Archean host, thus introducing yet an earlier set of dykes. Similarly, some of the dykes, sub-parallel to the gneissosity, may be earlier than the majority of the layer-discordant dykes. However, for purposes of discussion below, only dykes that obviously postdate the regional gneissic layering are dealt with here.

By analogy with the Nain Province at Saglek to the north and Hopedale to the south, it is proposed that some dykes are Early Proterozoic. Specific dykes of this age are, of course, difficult to identify in the field, but if the premise is valid, then some of the metadiabases must pre-date emplacement of the Middle Proterozoic NPS by 500 million years or more. Metamorphism and deformation could then be either pre-NPS or related to NPS (see below).

That some of the dykes must be Middle Proterozoic is based on the fact that amphibolite dykes like those in the gneisses occur within recrystallized and deformed metaplutonic rocks of the area that are considered to be members of the NPS. Dykes of this age are likewise difficult to pinpoint, but a few specific textural features may be diagnositc. For instance, those dykes with abundant clusters of skeletal plagioclase may be a variation on the snowflake textures seen in some of the NPS troctolitic rocks. Similarly, some dykes contain large megacrysts of black plagioclase that are identical to the feldspars in some olivine-bearing members of the anorthosite suite.

It is obvious that in order to distinguish the two intrusive episodes (Early versus Middle Proterozoic) in massive metamorphosed dykes, some criteria, perhaps a distinct geochemical fingerprint, must be found. If, as proposed above, there are Middle Proterozoic dykes, then it is possible that they may retain original geochemical characteristics that will provide important clues to the nature of the mantle and/or magma pond underlying this area at the time the NPS was being generated. Therefore, these dykes may provide another avenue to study the composition of the precursor magmas to the anorthosite suite.

Without adequate absolute age criteria it is also difficult to comment on intrusion mechanisms relative to Early or Middle Proterozoic emplacement. Features noted earlier indicate that some dykes appear to have been emplaced along active shear zones; other dykes display morphological attributes that imply emplacement into relatively hot and soft countryrock; other dykes exhibit a style that is consistent with emplacement under conditions of high hydrostatic pressure. It may not be too far-fetched to suggest that some of these features can be accommodated in an environment of anorthositic plutonism if the crust is 'softened' by heat liberated from an underlying magma pond at the crust–mantle interface, and that some of the leaking from this magma pond is being accomplished by way of hydrostatic fracturing and devolatization. Such fracturing may be induced by the fluids liberated as the lower crust was dehydrated above the magma pond. It is unlikely that the volatiles may be 'boiling off' the magma pond itself, since abundant evidence exists that the source magma for the anorthositic rocks was anhydrous.

It is perhaps appropriate at this point to address the deformation and metamorphism seen in the dykes. Using the present models of geological evolution of northern Labrador, two causes come to mind, viz. (i) a Lower Proterozoic (Hudsonian) overprint from events that produced the Churchill Province as outlined at the beginning of this paper, assuming the dykes are all Early Proterozoic, or (ii) tectonic and contact effects associated with the emplacement of the Middle Proterozoic plutons, assuming that the dykes are, in part, Middle Proterozoic in age. Each of these will now be considered.

It has been noted earlier that recent studies have shown that Hudsonian effects transgress eastward across northern Nain Province, such that the least imprint occurs in the Saglek–Nachvak area in the north and the greatest in the south at Okak (see for instance Ryan, 1990b; Ermanovics and van Kranendonk, 1990). At Okak, for instance, Early Proterozoic dykes display greenschist-facies metamorphism and deformation, attributed to Hudsonian overprint, some 50 km east of Churchill Province. Conceivably, therefore, the thermotectonic overprint in the dykes at Nain may be attributed to Hudsonian deformation. The metamorphism in the dykes examined this summer, however, shows plainly that these rocks have been at granulite facies, and such a degree of Hudsonian metamorphism is unknown east of the Churchill Province elsewhere in Labrador. Such a radical change in the character of Hudsonian overprint on the Nain Province here could only be accommodated by models such as one advocating overthrusting (cf. Wardle *et al.*, *in press*) of a (now eroded) thick slab of crust from the west during Hudsonian plate collision. It seems improbable therefore that the deformation and metamorphism seen in the dykes are entirely Early Proterozoic phenomena.

It is hard to escape the conclusion that some of the metamorphism and deformation must be Middle Proterozoic, concomitant with emplacement of the NPS. Accepting the premise that all the foliated and recrystallized noritic and anorthositic plutonic rocks described earlier in this paper are an integral part of NPS magmatism, then the foliated mafic dykes that occur within these units must owe their characteristics to events accompanying this magmatism. If mafic dykes occur within the plutons, in all likelihood equivalent mafic intrusions occur within the gneisses. A model to account for these features could entail early leaking from a subcrustal magma pond (Emslie, 1980) in the form of the dyke swarms. Emplacement of the anorthositic rocks probably occurred in pulses, separated by periods of renewed dyke intrusion. As a consequence of crustal processes active at this time, the dykes and plutons may then have undergone varying degrees of deformation and metamorphic recrystallization. This will be discussed further below.

It has previously been established that contact metamorphic aureoles of variable width are developed adjacent to the intrusive rocks of NPS. In all cases, these aureoles are statically developed; that is, the development of the contact aureole assemblages occurred under non-stressed conditions. This is especially evident in the Tasiuyak gneiss (Lee, 1987) and in paragneisses described in this paper, both of which contain cordierite–hypersthene pseudomorphs of garnet and cordierite–spinel pseudomorphs of sillimanite folia that preserve the ovoidal and lenticular characteristic, respectively, of the original regional metamorphic assemblage. This non-stress replacement of regional minerals in the Nain area is difficult to reconcile with the obvious development of penetrative fabrics in dykes that cut these same rocks. The most obvious solution is that the dykes were preferentially deformed because of the competency (and temperature?) difference between these intrusions and their host rocks allowed the dykes to deform more readily. Alternative explanations are (i) that the deformational fabrics in the dykes are in fact an artifact of Hudsonian (or earlier?) deformation that have not been eradicated by the pyroxene hornfels grade metamorphism or (ii) the fabrics are primary emplacement features, and the mineral assemblages in such dykes reveal crustal conditions at time of intrusion (amphibolite-facies dykes could thus postdate peak contact metamorphic conditions).

MODELS TO ACCOUNT FOR THE FEATURES SEEN IN THE FOLIATED ROCKS OF THE NPS

Foliated and recrystallized plutonic rocks within the NPS have not been specifically discussed in any great detail in previous literature on the anorthosite and granitoid rocks of the Nain region. As noted above, Wheeler simply assigned the foliated noritic rocks to a unit on his manuscript maps that he designated as 'granulite of uncertain origin'. However, in some cases, he realized that foliations occurred within rocks that otherwise had all other attributes of undeformed members of the NPS, and he concluded, as noted earlier, that these were indeed part of the NPS and that their structures represented protoclastic foliations and primary flow fabrics related to emplacement (see also Morse, 1969, p. 186). An outgrowth of his flow-fabric concept entailed emplacement of crystal mushes in the form of mushroom-shaped plutons (cf. Wheeler, 1969; Emslie *et al.*, 1972). This concept was enhanced and modified by de Waard (1973, 1974b, c, 1976) in which the deformational fabrics were accounted for by variations on gravitative collapse and/or density overturn within partially solidified igneous bodies, perhaps caused, in part, by diapiric piercement of older, partially crystallized rocks by younger, more buoyant plutons. Morse (1983b) has also used the concept of gravitational foundering and block rotation, caused by emplacement of younger magmas, to account for 'hot plastic stretching of megacrysts' in the Suzie Brook slab, a steeply dipping 9-km-wide unit of deformed leuconorite south of Tikkoatokak Bay. (This writer briefly examined this unit in 1989, and formed the impression that there is really no difference between the structure seen in these rocks and in the foliated norites seen between Webb Bay and Nain in 1990). A common thread running through all the above references is that the deformation of the plutonic rocks is a process intimately related to magmatic (emplacement) processes, not to post-crystallization events. This can also be seen, for instance, in Morse's (1983b, p. 39) conclusion that the development of a foliation in the Bird Lake Massif, also on Tikkoatokak Bay, suggests 'deformation before the end of crystallization', and Wiebe's (1976, p. 26) proposition that the major cause of 'considerable deformation' in anorthosite on Tunungayualok Island 'was most probably due to relative movement of adcumulates, orthocumulates and liquids within the developing anorthositic intrusion'.

Emslie (1985), in a wide-ranging overview of numerous Proterozoic anorthositic massifs, noted that recrystallization and deformation are not uncommon features in some intrusions, but because many of these intrusions occur within orogenic terranes having an obvious younger tectonic overprint, the origin of the foliations in the anorthosites is sometimes ambiguous. He does cite references to complexes in Norway and Quebec where the deformation and metamorphism have been attributed to diapiric emplacement of plagioclase-rich crystal mushes and/or fully consolidated plagioclase-rich plutons (see also papers by Duchesne and co-workers, *in* Maijer and Padget, 1987). Emslie proposed that buoyant rise of composite diapirs–an anorthositic core surrounded by a granitic envelope–was probably the mechanism by which all such plutonic suites are emplaced.

It is timely to note here a statement from Emslie's (op. cit, p. 57) review to the effect that '... although the existence of dispersed, bent, warped and kinked crystals has been widely observed in pristine massifs of central Labrador and elsewhere, evidence for large strain components in near solid anorthosite is not abundant.' From the data presented in this paper, it is now apparent that evidence of high strain is indeed present, and that the proportion of such rocks in the NPS has been underestimated. The presence of strongly deformed rocks in an area that has not ben affected by major orogenic events since the time of pluton emplacement should be used as a cautionary note when interpreting similar features of anorthositic rocks in areas that have been subjected to later regional deformation.

The degree and extent of deformation and recrystallization present in the NPS indicate that the cause of such features is an important factor to be considered in discussing the tectonic regime and emplacement mechanisms for these plutonic rocks. It is clear from the existing database (especially Wheeler's maps, and the NAP reports) that these are regional features in the NPS, not just locally developed phenomena. It is also probable that the deformation and metamorphism of the dykes in the gneisses is linked with the development of high-strain fabrics in the plutonic rocks.

It may be worthwhile to consider mechanisms other than primary flow fabrics, magmatic 'squeezing' and diapiric emplacement to account for the features observed in the NPS. While conceding that the following discussion is based on very limited data, and the diapiric model may be valid, an alternative model is considered to account for the relationships observed during the 1990 field season. This alternative model incorporates the basic concepts advocated for anorthosite intrusions already expounded by Emslie (1980), Morse (1982) and Wiebe (1990). It differs, however, in that it views the foliations and recrystallization seen in the plutonic rocks not as characteristics developed in an unconsolidated/incompletely crystallized magma mush, but rather as products of post-emplacement/post-crystallization deformation. The same tectonic regime that produced the strain fabrics in the NPS is also considered to be manifest in the deformation and metamorphism of the mafic dykes in the country rocks east of Nain.

The underlying 'engine' driving the anorogenic magmatism of the NPS is considered to be a subcrustal accumulation of tholeiitic magma that ascended from the mantle and spread along the crust-mantle interface. The crust was buoyed upward and subjected to localized extension, and dykes began to leak off the magma pond. As a consequence of the heat of crystallization, dehydration and anatexis of the overlying crust commenced. Another result of the increased heat flow from the subcrustal magma pond would have been that the crust became more ductile, thus providing environments in which the basic dykes could be emplaced both as planar and irregular bodies, in part, initiated by hydrostatic fracturing induced by the dehydration. Some of these dykes may in fact have crystallized with 'primary' metamorphic mineral assemblages; some may have been accompanied by granitoid melt and formed the composite dykes. Fractionation processes in the magma pond may ultimately have led to emplacement of hyperfeldspathic liquids into higher level magma chambers where they underwent final crystallization. These 'permitted' intrusions would have then imposed their thermal effects upon the surrounding crust, including the dykes that had previously tapped the magma pond below. A long-lived basic magmatic event of this type would lead to several discrete generations of basic dykes in the country rock and also to earlier crystallized plutons being cut by basic dykes produced by the periodic leaking of magma from the underlying replenished subcrustal pond. Any particular voluminous magma intrusive event would not only include anorthositic rocks, but also the ever-present ferrodioritic and granitic members. Thus, within the NPS as a whole, there should be a variation in the absolute age of particular members, e.g., both older and younger basic dykes and rapakivi granites should exist.

The formation of the foliations in the anorthositic and other plutonic rocks of the NPS is considered to be a function of tectonic events that affected them shortly after their emplacement and crystallization. Current models of the tectonic setting for the NPS advocate an extensional regime (cf. Berg, 1977b), but regional geological considerations imply very limited lateral motion and suggest instead that perhaps subvertical movement (megablock stoping) played a key role in promoting and permitting magma emplacement (cf. Ryan, *in press*). It is logical that during the limited extensional regime under which the anorogenic magmatism was occurring, there would be long-lived, but periodic, formation of extensional faults and shear zones. These may have been triggered by episodic magma underplating at the base of the crust. The deformation caused by these extensional crustal events would, of course, affect members of the plutonic suite already emplaced. It appears that the contact zones between the plutons and the enveloping gneisses were intensely deformed during such movements, perhaps in a manner analagous to core complexes where crustal extension caused the country rock to slide off the plutonic core. Extensional (?) lineations are locally well developed, for instance in deformed plutonic rocks of the Anaktalik Bay area and at Webb Bay; they are consistently moderately S-plunging in all cases.

In some cases, as at Webb Bay, the deformed noritic rocks are intruded by post-deformational granite dykes. The fact that these felsic dykes are recrystallized in the same manner as the host implies that the polygonization of the deformed anorthositic rocks occurred as a post-deformational event. This static recrystallization is considered to have been triggered either by the ambient high heat-flow from the subcrustal magma pond, or else by renewed heating of the deformed plutonic rocks by the local arrival of new magma. That ductile shearing was imposed upon the plutonic rocks, in some cases after emplacement of mafic dykes, is demonstrated by the shear zones seen in the Georges Island–Challenger Cove noritic rocks. Similar intrapluton shearing is shown by anorthositic rocks on Paul Island (de Waard, 1974c, p. 281). Of interest here too, is the observation that in these zones in the Georges Island–Challenger Cove area the noritic rocks and the dykes are amphibolitized, implying access of external aqueous fluids into otherwise 'dry' rocks. The concept of post-emplacement zonal hydration also addresses Morse's (1983b, p. 41) dilema regarding biotite along the western margin of the Bird Lake massif, and accounts for the biotite-bearing saccharoidal anorthosite observed on Noazunakuluk Island, since it still allows for the original 'dry' magmas demanded by the regional contact metamorphic assemblages.

The deformation and recrystallization in the NPS is considered to be post-emplacement and post-crystallization for several reasons. Chief among these is that there is no firm evidence in any of the anorthositic rocks examined this summer that these rocks were ever mushes at time of deformation. On the contrary, all indications favour the argument that they were in fact crystalline. For example, there is no evidence of any residual liquid having been expelled, as would be expected in the case of deformation of a crystal mush. There is, however, abundant evidence that pyroxene had already crystallized in a subophitic habit prior to deformation. This can be readily demonstrated by the progressive deformation of 'diabasic' textures in shear zones and by the fact that the larger pyroxene lozenges in the deformed rocks retain their original massive solid cores whereas their margins are deformed and subsequently annealed. A similar argument can be used for the foliated rapakivi rocks north of Anaktalik Brook in which large feldspar augen are surrounded by a fine, granular, annealed matrix that preserves the foliation outlined by streaks of mafic minerals. There is no indication of the primary megacryst alignment that would be expected from magmatic flow; instead the field textures suggest post-consolidation deformation of the granitoid, followed by post-deformation recrystallization.

The less-deformed state of the plutonic rocks on the outer islands may indicate these are relatively later intrusions, that were perhaps subjected only to weak stress during the waning stages of the regional extensional regime (e.g., the foliated margin to the Dog Island ferrodiorite, the foliated anorthosite zone on Noazunakaluk Island). The gneisses into which these plutonic rocks are emplaced similarly appear to have escaped any profound Middle Proterozoic deformation; however, the basic dykes have been preferentially affected. Their deformation in shear zones and development of sigmoidal foliations and lineations is again suggestive of the influence of a regional shear regime. The geometry of the foliation in the dykes of the Sandy Island–Dog Island area noted earlier suggests that in this area a component of extensional shear was oriented northwest–southeast.

The preservation of original garnet and sillimanite shapes in the paragneisses, despite obvious contact metamorphic replacement by secondary minerals, and the lack of regional fold patterns that can be attributed to pluton emplacement, suggest a subordinate role for compressive stress during igneous activity. This is counter to what would be expected in the local area if forceful diapirism was active. Similarly, the vast majority of dykes oriented normal to pluton margins in the area are not anomalously affected by folding or deformation near the plutons; in a diapiric regime one would expect such dykes to be tightly folded and disrupted in proximity to the plutons.

It is perhaps of interest to note that on a regional scale the gneisses have retained their pre-Middle Proterozoic trends in spite of their setting as a narrow septum between batholithic masses of anorthositic and granitic rocks of the NPS. This relationship may also be used to argue against diapiric emplacement of the plutonic rocks, for in this model it is difficult to see how such a narrow gneissic zone could have escaped being drawn into conformability with the margins of the plutonic rocks. Instead the plutons plainly transect, without disturbing, the original fold patterns in the gneissic envelope. Therefore, it implies passive emplacement of the plutonic rocks, a mechanism also implied by the large dykes of granite on northern Dog Island and nearby islands, which appear to have been emplaced as a result of extensional fracturing of the gneisses.

Therefore, it seems that some of the deformed and metamorphosed mafic dykes of the outer islands, and the deformed rocks of the NPS west and north of Nain, are products of the same dynamic process. Dykes, intruded into a hot and ductile crust of gneisses as a result of leaking from a subcrustal magma pond, may have been subsequently deformed and metamorphosed in shear zones associated with the emplacement of the magmas that produced the regional NPS. Mafic dykes episodically penetrated the earliest plutons, and the whole complex was then deformed by subsequent shear-related deformation, with the strongest fabrics appearing to have developed along the original interface between the plutons and the gneisses, perhaps in a tectonic regime not unlike that of core complexes. Repeated intrusion, deformation, and recrystallization is indicated; part of the deformation and recrystallization occurred under conditions conducive to the development of hydrous phases in the plutons themselves. The episodic emplacement and deformation/recrystallization of the plutonic rocks can explain deformed plutons crosscut by undeformed ones and account for fragments of older deformed and recrystallized rocks entrained in younger plutons (cf. Wiebe, 1976; Davies, 1975). A mechanism of this type also predicts that some deformed plutons should contain fragments of even older deformed plutonic rocks, as a result of the repetitive intrusion and deformation.

The proposal of post-emplacement deformation outlined above overcomes some of the problems associated with the diapiric model. For instance, if anorogenic plutons are characteristically emplaced as diapirs—why do all such rocks of the NPS not display foliate margins? Similarly, in areas where two plutonic rocks are of different relative age, why do they carry a common fabric? The simplest explanation is that at time of emplacement, none of the plutonic rocks displayed such features; the foliations were imposed later. Post-crystallization shear-zone-type deformation in the interior of the anorthosite terrane could also account for extensive areas of such rocks described in NAP reports, for instance, the Suzie Brook slab (Morse, 1983b) and foliated anorthosite in the Port Manvers Run area (Berg, 1974), and for zones of 'granulite of uncertain origin' shown on E.P. Wheelers manuscript maps in the area between Kingurutik Lake and Anaktalik Brook. The youngest plutons of the NPS, that is those emplaced during the final stages of crustal extension, still show their primary intrusive discordant contacts because they have not been subsequently modified by the deformational processes related to crustal movement that had affected the older members.

SUMMARY

The 1990 field investigations of the Nain area have suggested a re-evaluation of existing models for the geological evolution of this part of Labrador. In particular, the work has documented a regional swarm of metamorphosed and foliated mafic dykes, and prompted the proposal that some of these dykes are in fact representatives of the basic magmatism that is manifested on a more obvious regional scale as the anorthositic and related rocks of the NPS. The work has shown also that significant areas of the NPS have been subjected to post-crystallization deformation and recrystallization. It is suggested that the deformed/metamorphosed mafic dykes and the foliated plutonic rocks are products of the same process, both being generated by limited, episodic extensional shear during the Middle Proterozoic when the NPS was emplaced.

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REFERENCES

Berg, J.H.
1973: Geology of the Hettasch Lake area. *In* The Nain Anorthosite Project, Labrador: Field Report, 1972. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 11, pages 49-64.

1974: Further study of the Hettasch Intrusion and associated rocks. *In* The Nain Anorthosite Project: Field Report, 1973. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 13, pages 107-119.

1977a: Dry granulite mineral assemblages in the contact aureoles of the Nain Complex, Labrador. Contributions to Mineralogy and Petrology, Volume 64, pages 33-52.

1977b: Regional geobarometry in the contact aureoles of the anorthosite Nain Complex, Labrador. Journal of Petrology, Volume 18, pages 399-430.

1980: Snowflake troctolite in the Hettasch Intrusion Labrador: Evidence for magma-mixing and supercooling in a plutonic environment. Contributions to Mineralogy and Petrology, Volume 72, pages 339-351.

Berg, J.H. and Briegel, J.S.
1983: Geology of the Jonathon intrusion and associated rocks. *In* The Nain Anorthosite Project, Labrador: Field Report, 1981. *Edited by* S.A. Morse. Department of Geology and Geography, Contribution No. 40, pages 43-50.

Brand, S.
1975: The geology of the Lower Khingughutik River. *In* The Nain Anorthosite Project, Labrador: Field Report, 1974. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 17, pages 48-57.

1976: Geology, petrology and geochemistry of the Lower Kingurutik River area, Labrador, Canada. Unpublished Ph.D. thesis, Purdue University, W. Lafayette, Indiana, 265 pages.

Bridgwater, D., Mengel, F., Schiotte, L. and Winter, J.
1990: Research on the Archean rocks of northern Labrador, progress report 1989. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 227-236.

Chadwick, B. and Coe, K.
1983: Buksefjorden, 63V.1 Nord: The regional geology of a segment of the Archean block of southern West Greenland. Descriptive text to 1:100,000 sheet. Gronlands Geologiske Undersogelse, 70 pages.

Currie, K.L. and Ferguson, J.
1970: The mechanism of intrusion of lamprophyre dikes indicated by 'offsetting' of dikes. Tectonophysics, Volume 9, pages 525-535.

Daly, R.A.
1902: The geology of the northeast coast of Labrador. Bulletin of the Museum of Comparative Zoology of Harvard University, Volume 38, Geological Series 5, pages 205-270.

Davies, H.M.
1975: Emplacement sequence of anorthositic rocks in the southeastern portion of the Nain Complex. *In* The Nain Anorthosite Project, Labrador: Field Report, 1974. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 17, pages 58-66.

de Waard, D.
1969: Annotated bibliography of anorthosite petrogenesis. *In* Origin of Anorthosite and Related Rocks. *Edited by* Y.W. Isachsen. New York State Museum Science Service Memoir 18, Albany, New York, pages 1-11.

1971: Country-rock of the anorthosite massif and anorthosite contacts in the Ford Harbour region. *In* The Nain Anorthosite Project, Labrador: Field Report, 1971. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 9, pages 15-26.

1973: Contact relationships of adamellitic intrusions on Dog Island. *In* The Nain Anorthosite Project, Labrador: Field Report, 1972. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 11, pages 37-41.

1974a: On the nomenclature and classification of rock groups in the Nain anorthosite complex (continued). *In* The Nain Anorthosite Project, Labrador: Field

Report, 1973. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 13, pages 41-44.

1974b: Anorthosite-adamellite contact on Dog Island, Labrador. *In* The Nain Anorthosite Project, Labrador: Field Report, 1973. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 13, pages 63-72.

1974c: Structures in the Nain Complex, Labrador, and their bearing on the origin of anorthosite. Koninklijke Nederlandse Akademie van Wetenschappen, Proceedings Series B, pages 274-285.

1976: Anorthosite-adamellite-troctolite layering in the Barth Island structure of the Nain complex, Labrador. Lithos, Volume 9, pages 293-308.

Emslie, R.F.

1980: Geology and petrology of the Harp Lake Complex, central Labrador: an example of Elsonian magmatism. Geological Survey of Canada, Bulletin 293, 136 pages.

1985: Proterozoic anorthosite massifs. *In* The Deep Proterozoic Crust in the North Atlantic Provinces. *Edited by* A.C. Tobi and J.L.R. Touret. NATO Advanced Sciences Institute, Series C, 158, pages 39-60.

Emslie, R.F. and Hunt, P.A.

1990: Ages and petrogenetic significance of igneous-charnockite suites associated with massif anorthosites, Grenville Province. Journal of Geology, Volume 98, pages 213-232.

Emslie, R.F., Morse, S.A. and Wheeler, E.P.

1972: Igneous rocks of central Labrador with emphasis on anorthositic and related intrusions. Guidebook, Field Excursion A54, 24th International Geological Congress, 72 pages.

Ermanovics, I.F. and van Kranendonk, M.

1990: The Torngat Orogen in the North River–Nutak transect area of Nain and Churchill provinces. Geoscience Canada, Volume 17, pages 279-283.

Harris, A. (Compiler)

Geological map of Tasisuak Lake. Newfoundland Department of Mines and Energy, Mineral Development Division, 1:200,000 scale. Map 80-13.

Jackson, M.P.A. and Zelt, G.A.D.

1984: Proterozoic crustal reworking and superposed deformation of metabasite dykes, layered intrusions, and lavas in Namaqualand, South Africa. *In* Precambrian Tectonics Illustrated. *Edited by* A. Kröner and R. Greiling. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pages 381-400.

Lee, D.V.

1987: Geothermobarometry and petrologic history of a contact metamorphosed section of the Tasiuyak Gneiss, west of Nain, Labrador. Unpublished B.Sc. dissertation, Memorial University of Newfoundland, St. John's, 111 pages.

Maijer, C. and Padget, C.

1987: The geology of southernmost Norway: an excursion guide. Norges Geologiske Undersokelse, Special Publication No. 1, 109 pages.

Meyers, R.E. and Emslie, R.F.

1977: The Harp dikes and their relationship to the Helikian geological record in central Labrador. Canadian Journal of Earth Sciences, Volume 14, pages 2683-2696.

Morse, S.A.

1969: Layered intrusions and anorthosite genesis. *In* Origin of Anorthosite and Related Rocks. *Edited by* Y.W. Isachsen. New York State Museum Science Service, Memoir 18, Albany, New York, pages 175-187.

1971-1983: Nain Anorthosite Project, Labrador: Field Reports. Department of Geology, University of Massachusetts, Amherst, Contributions 9, 11, 13, 17, 26, 29, 38 and 40.

1982: A partisan review of Proterozoic anorthosites. American Mineralogist, Volume 67, pages 1087-1100.

1983a: Emplacement history of the Nain Complex. *In* The Nain Anorthosite Project, Labrador: Field Report, 1981. *Edited by* S.A. Morse. Department of Geology and Geography, University of Massachusetts, Contribution No. 40, pages 9-15.

1983b: Reconnaissance geology of the Bird Lake massif, Labrador. *In* Nain Anorthosite Project, Labrador: Field Report, 1981. *Edited by* S.A. Morse. Department of Geology and Geography, University of Massachusetts, Amherst, Contribution No. 40, pages 37-41.

Nash, D.

1979: An interpretation of irregular dyke forms in the Itivdleq shear zone, West Greenland. Gronlands Geologiske Undersogelse, Report 89, pages 77-83.

Planansky, G.A.

1971: The Bridges layered series and associated anorthosites. *In* The Nain Anorthosite Project, Labrador: Field Report, 1971. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 9, pages 47-60.

Pollard, D.D.
1987: Elementary fracture mechanics applied to the structural interpretation of dykes. *In* Mafic Dyke Swarms. *Edited by* H.C. Halls and W.F. Fahrig. Geological Association of Canada, Special Paper 34, pages 5-24.

Pollard, D.D., Muller, O.H. and Dockstader, D.R.
1975: The form and growth of fingered sheet intrusions. Geological Society of America Bulletin, Volume 86, pages 351-363.

Rubins, C.C.R.
1971: The Barth Island troctolite body; granulite-adamellite-anorthosite relations at the northern margin. *In* The Nain Anorthosite Project, Labrador: Field Report, 1971. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 9, pages 34-42.

Ryan, B.
1990a: Geological map of the Nain Plutonic Suite and surrounding rocks (Nain-Nutak, NTS 14SW). Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-44, scale 1:500,000.

1990b: Basement-cover relationships and metamorphic patterns in the foreland of Torngat Orogen in the Saglek-Hebron area, Labrador. Geoscience Canada, Volume 17, pages 276-279.

In press: Makhavinekh Lake pluton, Labrador, Canada: geological setting, subdivisions, mode of emplacement and a comparison with Finnish rapakivi granites. Precambrian Research.

This volume: Nain—Nutak area: a new 1:500,000-scale colour compilation.

Ryan, B. and Lee, D.
1986: Gneiss-anorthosite granite relationships in the Anaktalik Brook-Kogaluk River area (NTS 14D/1,8), Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 79-88.

Taylor, F.C.
1979: Reconnaissance geology of a part of the Precambrian Shield, northeastern Quebec, northern Labrador and Northwest Territories. Geological Survey of Canada, Memoir 393, 99 pages.

Upton, B.G.J.
1971: Basic dykes. *In* The Nain Anorthosite Project, Labrador: Field Report, 1971. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 9, pages 66-67.

1974: Basic dykes in the Nain-Kiglapait region. *In* The Nain Anorthosite Project, Labrador: Field Report, 1973. *Edited by* S.A. Morse. Department of Geology, University of Massachusetts, Contribution No. 13, pages 133-143.

Wager, L.R. and Brown, G.M.
1967: Layered Igneous Rocks. Freeman, San Francisco, 588 pages.

Wardle, R.J., Ryan, B., Nunn, G.A.G. and Mengel, F.C.
In press: Labrador segment of the Trans-Hudson Orogen: crustal development through oblique convergence and collision. *In* The Early Proterozoic Trans-Hudson Orogen: Lithotectonic Correlations and Evolution. *Edited by* J.F. Lewry and M.R. Stauffer. Geological Association of Canada, Special Paper 37.

Watterson, J.
1968: Plutonic development of the Ilordleq area, south Greenland, Part II: late kinematic basic dykes. Meddelelser om Gronland, Bd. 185, 104 pages.

Wheeler, E.P.
1933: A study of some diabase dikes on the Labrador coast. Journal of Geology, Volume 41, pages 418-431.

1942: Anorthosite and related rocks about Nain, Labrador. Journal of Geology, Volume 50, pages 611-642.

1955: Adamellite intrusive north of Davis Inlet, Labrador. Geological Society of America, Bulletin 66, pages 1031-1060.

1960: Anorthosite-adamellite complex of Nain, Labrador. Geological Society of America, Bulletin 71, pages 1755-1762.

1969: Minor intrusives associated with the Nain anorthosite. *In* Origin of Anorthosite and Related Rocks. *Edited by* Y.W. Isachsen. New York State Museum Science Service, Memoir 18, Albany, New York, pages 189-206.

Wheeler, E.P. and Morse, S.A.
1973: Deformational history of the Ford Harbour Formation. *In* The Nain Anorthosite Project, Labrador: Field Report, 1972. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 11, page 117.

Wiebe, R.A.
1976: Geology of northern Tunungayualok Island and vicinity. *In* The Nain Anorthosite Project, Labrador: Field Report, 1974. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 17, pages 37-47.

1981: Eastern margin of an anorthosite pluton on Paul Island. *In* The Nain Anorthosite Project, Labrador: Field Report, 1980. *Edited by* S.A. Morse. Department of Geology, University of Massachusetts, Contribution No. 38, pages 35-40.

1985: Proterozoic basalt dykes in the Nain anorthosite complex, Labrador. Canadian Journal of Earth Sciences, Volume 22, pages 1149-1157.

1990: Evidence for unusually feldspathic liquids in the Nain Complex, Labrador. American Mineralogist, Volume 75, pages 1-12.

Williams, G.L., Fyffe, L.R., Wardle, R.J., Colman-Sadd, S.P., Boehner, R.C. and Watt, J.A. (Editors)
1985: Lexicon of Canadian Stratigraphy, Volume VI: Atlantic Region. Canadian Society of Petroleum Geologists, 572 pages.

Woodward, C.
1973: Newark Island layered complex. *In* The Nain Anorthosite Project, Labrador: Field Report, 1972. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 11, pages 42-48.

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ON RECENT GEOCHRONOLOGICAL STUDIES IN THE NAIN PROVINCE, CHURCHILL PROVINCE AND NAIN PLUTONIC SUITE, NORTH-CENTRAL LABRADOR

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ABSTRACT

U−Pb geochronology has been undertaken on a variety of rocks between Voisey Bay and the Quebec border. The gneisses along the coast maintain some attributes of their Archean, Nain Province heritage, but an Early and Middle Proterozoic isotopic overprint is obvious. Rocks within the Churchill Province yield zircon, titanite and monazite that point to Archean protoliths overprinted by high-grade metamorphism ca. 1830-1800 Ma. Early Proterozoic juvenile crust is subordinate to Archean crust in the suite of rocks examined from the Churchill Province. Posttectonic granitoid plutons yield ages consistent with their field interpretation as Elsonian intrusions.

INTRODUCTION

A four-year mapping program, from Voisey Bay westward to the Quebec border, was completed in 1988. The 60-km-wide transect covers Archean gneisses of the Nain Province, Early Proterozoic and reworked Archean gneisses of the Churchill Province and Middle Proterozoic plutonic rocks of the Nain Plutonic Suite (Figure 1). Since only limited geochronological data, in the form of potassium−argon mineral ages, were available from this area, a U−Pb zircon program was initiated in order to obtain some idea of the absolute age of specific rock units and to establish a relative chronology of events determined from field studies. This paper summarizes some of the results from the geochronological program, conducted over a 3-year period, mostly at the zircon-dating laboratory of the Royal Ontario Museum (ROM), Toronto. The less-complete data referred to herein arise mainly from work still in progress by U. Schärer and S. Philippe. Geological details relevant to the following discussion may be found in papers by Ryan and Lee (1986), Ryan *et al.* (1987, 1988) and Ryan (1990). Data and graphical representations of the age studies carried out at the ROM are on file at the Geological Survey Branch of the Newfoundland Department of Mines and Energy (Krogh and Schärer, 1987; Krogh and Heaman, 1989; Krogh and Oliver, 1990). More discussion of the data and the regional significance of the results of these studies will be presented in papers to be published elsewhere.

The capitalized letters following the sample reference numbers in the text below and also in Table 1 refer to the sample sites shown on Figure 1.

RESULTS

NAIN PROVINCE

Rocks assigned to the Nain Province occupy the coastal strip north of Voisey Bay. These have been overprinted by Early Proterozoic tectonothermal activity, a conclusion initially proposed on the basis of field observation that mafic dykes of Early Proterozoic age within these gneisses are deformed and are metamorphosed to amphibolite facies. Study of samples from a coastal outcrop of grey migmatite containing a folded amphibolite dyke gave the following results:

Zircon from one sample (Nain 2,A) of the grey migmatite defines a mixing line with an upper intercept age of 2843 ± 11 Ma and a lower intercept age of 1805 Ma. The older age is considered to reflect the Archean protolith age of the migmatite, whereas the 1805 Ma falls within the range of a metamorphic episode in the Churchill Province (see below).

Preliminary analysis of another sample (US.87.21,A) from the same outcrop has yielded a thorite(?) population that gives a much younger age, namely 1310 ± 5 Ma. This appears to reflect thermal resetting and/or new growth caused by a nearby rapakivi granite pluton (see below).

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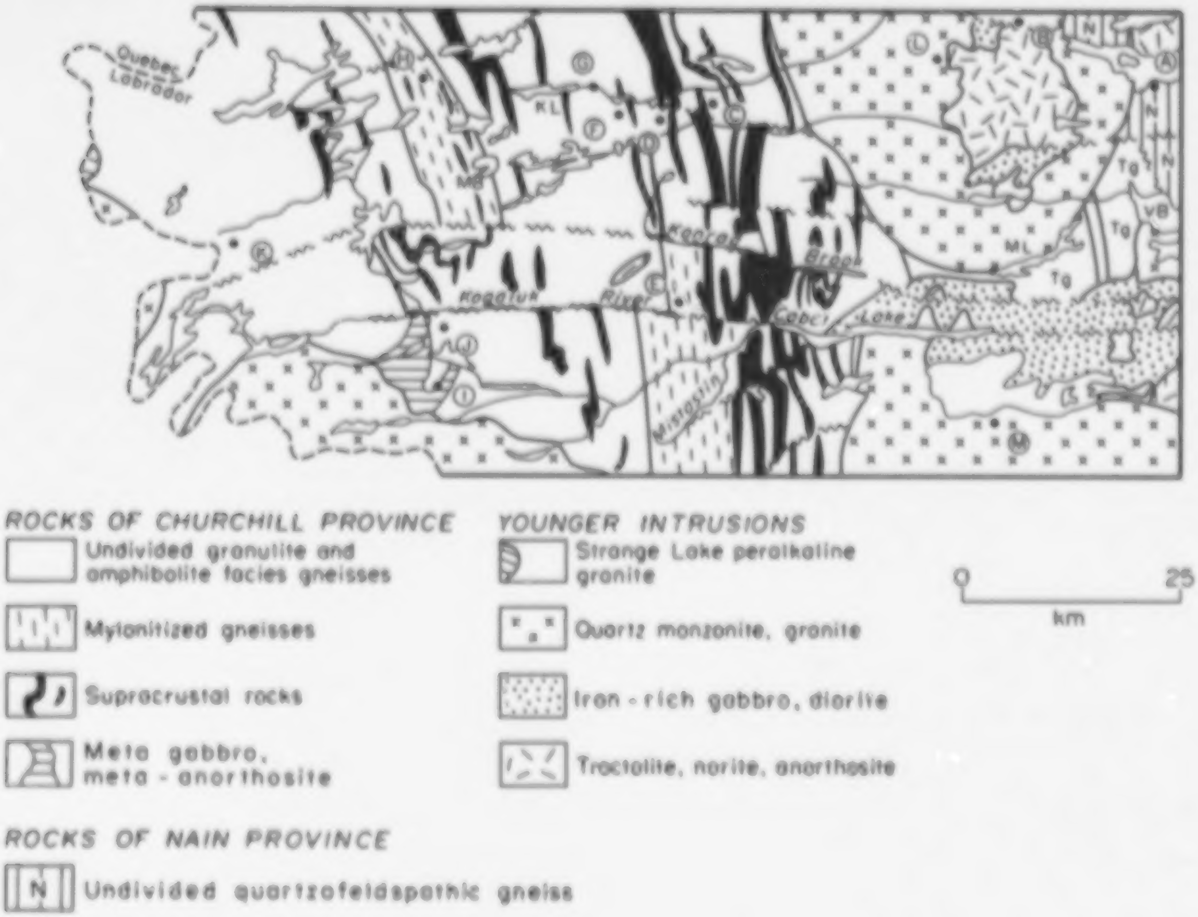
Quebec
Labrador
KL
MB
ML
Tg
VB
N
Kogaluk River
Brook
Cabot Lake
Mistastin
A
B
C
D
E
F
G
H
I
J
K
L
M
ROCKS OF CHURCHILL PROVINCE
Undivided granulite and amphibolite facies gneisses
Mylonitized gneisses
Supracrustal rocks
Meta gabbro, meta - anorthosite
YOUNGER INTRUSIONS
Strange Lake peralkaline granite
Quartz monzonite, granite
Iron - rich gabbro, diorite
Troctolite, norite, anorthosite
ROCKS OF NAIN PROVINCE
Undivided quartzofeldspathic gneiss
0
25
km

Figure 1. *Sketch map of the Nain Province–Churchill Province transect showing sample sites for geochronology studies. Circled letters with dot refer to sample locations and numbers listed in text and Table 1. Tg = Tasiuyak gneiss, VB = Voisey Bay, ML = Makhavinekh Lake, KL = Khongnekh Lake, MB = Moonbase Lake.*

The folded amphibolite dyke (Nain 3,A) yielded three zircon fractions, which define a line with upper intercept of 2100 ± 100 Ma and lower intercept of 1434 ± 4 Ma. Titanite from the same sample gives an age of 1256 ± 6 Ma. It is probable that the older zircon age from the dyke marks the age of intrusion, and that the titanite age marks the waning thermal effects of the rapakivi intrusion. The significance of the 1434-Ma age is somewhat obscure at present, but it is of interest to note that it falls within the time frame of some of the earliest Elsonian intrusions in central Labrador (for example 1448 to 1447 Ma for Harp Lake 'adamellite', 1426 Ma for Snegamook granite; see Stockwell, 1982, p. 63) and may be a record of resetting during this early phase of the Elsonian anorogenic magmatism. Alternatively, the older zircons may be xenocrystic and the younger ones give the actual age of the dyke emplacement.

CHURCHILL PROVINCE

The Churchill Province includes the 30-km-wide Tasiuyak gneiss and its intercalated enderbitic units that lie immediately west of Nain Province, and the polylithologic complex of gneisses and foliated charnockitic rocks that lie to the west of Tasiuyak gneiss. The Churchill Province contains a significant proportion of Hudsonian-reworked Archean crust, the Rae Province of Hoffman (1988). A suite of layered gneisses and foliated plutonic rocks from the Churchill Province has been investigated by U–Pb geochronology. Results are as follows:

A schlieric-layered, lineated, enderbitic gneiss occurs north of a polyphase Elsonian intrusion in eastern Churchill Province. Three zircon fractions from a sample (BR.85.259,B) of this rock plot on a line with an upper intercept of $1909^{+\text{[illegible]}}_{-\text{[illegible]}}$ Ma and a lower intercept of $1307^{+\text{[illegible]}}_{-\text{[illegible]}}$ Ma. Both these ages are somewhat difficult to explain in light of the known regional geology, since they do not correlate with any known metamorphic or intrusive events in this part of Labrador. It may be that the overprinting pyroxene–hornfels contact metamorphism from nearby anorthositic and granitic plutons has disturbed the P–Ub zircon systematics and these dates do not represent meaningful geological events.

Table I. Summary of geochronological results. See text for discussion of data. Letters refer to sample localities on Figure 1

Locality (Figure 1)	Sample	Minerals	Age [Upper Intercept / Lower Intercept] Ma	Comments
A	Nain 2 qtz-felds gneiss	zircon	2843 ± 11 1805	mixing line, Archean protolith, Hudsonian overprint
A	US.87.21 qtz-felds gneiss	thorite(?)	1310 ± 5	preliminary data, Middle Proterozoic thermal resetting
A	Nain 3 amphibol. dyke	zircon titanite	2100 ± 100 1434 ± 4 1256 ± 6	older age may be time of intrusion; younger ages reflect thermal disturbance
B	BR.85.259 opx-qtz-felds gneiss	zircon	$1909^{+[illegible]}_{-[illegible]}$ $1507^{+[illegible]}_{-[illegible]}$	thermal disturbance of zircon by granite?
C	Geo.89.4 noritic pegmatite	zircon, monazite	1831 ± 2 1803	older age may be pegmatite crystallization age
D	Geo.89.3 massive charnockite	zircon, monazite	$2597^{+[illegible]}_{-[illegible]}$ 1823	Archean intrusion?
E	Geo.89.5 mylonitized gneiss	zircon, titanite	$2572^{+[illegible]}_{-[illegible]}$ 1806	mylonitized Archean gneiss
F	Geo.89.2 sillimanite-biotite augen gneiss	zircon, monazite	2574 ± 8 1824	Archean intrusion?
G	Geo.89.1 qtz-felds gneiss	zircon, monazite zircon	2657 ± 18 1824 1975	Archean migmatite with Proterozoic overprint
H	US.87.29 mylonitized gneiss	thorite(?)	1857 ± 3	preliminary data, Proterozoic metamorphism?
I	US.87.27 qtz-felds gneiss	zircon	$2807^{+[illegible]}_{-[illegible]}$	preliminary data
J	DD.87.48b pegmatite	zircon	1854 ± 1	intrusion age
K	BR.87.336 pink granite	zircon, monazite	$1859^{+[illegible]}_{-[illegible]}$ 1990 231 1760 1841 1837	complex zircon population
L	DL.85.201 rapakivi granite	zircon	1322 ± 1 117	older age is time of intrusion
M	US.87.26 granite	zircon	1292 ± 4	preliminary data intrusion age

A weakly foliated, pegmatitic leuconoritic dyke (Geo.89.4,C) intrudes a metamorphosed and gneissose anorthositic and noritic layered intrusion, and is probably related to the larger layered body itself. Low U zircons from a sample of this dyke indicate a primary (intrusion ?) age of 1831 ± 2 Ma. Monazite growth occurred at around 1803 Ma. If the dyke is genetically related to the larger layered unit in which it occurs, it implies basic magmatism at about 1830 Ma in this area. Monazite and titanite from other rocks in this general area (see below) suggest high-grade metamorphism around this time as well, indicating a coeval magmatic–metamorphic episode whose influence may have lasted until ca. 1800 Ma.

Weakly foliated, fairly homogeneous, medium-grained charnockite is not uncommon in parts of central Churchill Province. One sample (Geo.89.3,D) was collected from a fairly extensive unit of this rock type. This rock differs radically from well-layered migmatite in the same general area, and was considered, on the basis of its weakly foliated character, to be a late kinematic Hudsonian intrusion. The line defined by the zircon populations (which fall well off concordia) may be interpreted to suggest an Archean protolith (upper intercept) of 2597[illegible] Ma, which has been subjected to high-grade metamorphism in the Early Proterozoic (lower intercept of 1823 Ma controlled by a monazite analysis), or else inherited zircons in a Proterozoic intrusion.

One sample (Geo.89.5,E) of mylonitized gneiss from a broad amphibolite facies, high-strain zone near Mistastin River has been investigated. An upper intercept age of 2572[illegible] Ma is obtained, when projected to the titanite age of 1806 Ma, and is interpreted to provide more evidence of Archean crust affected by metamorphism and mylonitization during the Early Proterozoic.

Zircon fractions isolated from sillimanite–biotite augen gneiss (Geo.89.2,F), associated with rusty garnetiferous pelitic gneiss, cluster near concordia. It is not possible to determine in the field if this is a highly deformed porphyritic granite within the paragneiss or a porphyroblastic variety of the metasedimentary rocks. A line, hinged on 1824 Ma monazite from the same rock, gives an upper intercept age of 2574 ± 8 Ma. The simple single-zircon population from this rock is consistent with the interpretation that this unit is a simple granite, although this poses some problems in interpreting the significance of the older age here. Although not ruling out the existence of Archean supracrustal rocks, it is assumed that most of the supracrustal rocks within the inner Churchill (Rae) Province are Lower Proterozoic cover that have been interleaved with reworked basement. However, the simple-zircon population for this rock seems to indicate that this granite could have been derived from the surrounding paragneiss during the late Archean, and then deformed and metamorphosed during Hudsonian events. Again, as with some of the other rocks, the data may indicate inherited zircons of Archean age in a granite emplaced at 1824 Ma, but it would seem unlikely that inherited zircons would produce a well-defined cluster near concordia, as the population from this rock does, unless they are all from the same original source.

Grey, amphibolite-facies migmatite, containing generally concordant amphibolite dykes, occupies much of the region east of the Moonbase Lake mylonite zone. One sample of grey migmatite (Geo.89.1,G) was collected from this region. Six zircon fractions, with an extrapolated line from an 1824 Ma monazite (from Geo.89.2), give an upper intercept of 2657 ± 18 Ma. A line through the zircons alone suggests growth around 1975 Ma, the significance of which is unclear. Neosomal zircons from the sample plot farther down the discordia line than paleosomal zircons, suggesting new growth during metamorphism.

Highly strained, regularly banded, grey gneiss and parallel amphibolite-mafic granulite dykes characterize the northern part of the Moonbase Lake mylonite zone. Grey gneiss (US.87.29,H) from this zone has yielded thorite(?) that suggests high-grade metamorphism at 1857 ± 3 Ma, 50-million years older than the age determined for metamorphism in the Mistastin River zone noted above.

West of the Moonbase Lake mylonite zone, it is not uncommon to find metamorphosed, highly discordant dykes in the gneisses. These gneisses and pre-dyke metamorphosed leucogabbro–anorthosite units within them, were postulated, on the basis of field relations and comparison with Nain Province geology, to be Archean in age. Preliminary results from poor-quality zircons from one sample (US.82.27,I) of gneiss that hosts leucogabbro fragments yields an imprecise age of 2807[illegible] Ma.

A weakly deformed biotite pegmatite dyke (DD.87.48b,J), discordant to gneisses that contain leucogabbro fragments and that are cut by basic granulite dykes, has yielded large equant zircon grains that are nearly concordant at 1854 ± 1 Ma, and this is interpreted as the time of dyke emplacement. This dyke is identical to pegmatites that form an intrusive network in a large granulite-facies mafic dyke in a nearby outcrop, and is therefore assumed to have been emplaced after the peak of granulite-facies metamorphism. It should be noted that this age corresponds to the time of high-grade metamorphism in the Moonbase Lake mylonite zone, but here appears to signify granitic intrusion that postdates an earlier granulite-facies event.

A small, weakly foliated pink granite (BR.87.336,K), concordant to gneissosity on a regional scale and assumed to be late kinematic with respect to Hudsonian deformation and metamorphism, yielded a complex population of zircon and monazite. Two zircon fractions fall well off concordia and define a line with upper intercept of 1859[illegible] Ma and lower intercept of 231 Ma. Two monazite fractions plot close to concordia at 1851 Ma and 1837 Ma; a line through these gives 1990 Ma and 1760 Ma as upper and lower intercepts, respectively. Two explanations for these relationships are possible: (i) the upper monazite age is the time of emplacement and the younger is the time of metamorphism, the zircons having been moved off the line by recent Pb loss and hence giving meaningless ages, or (ii) the 1760 Ma age is the time of granite emplacement and both the older monazite and the zircon population are inherited, making the similarity in age between the above pegmatite (1856 Ma) and this granite (1859 Ma) purely fortuitous.

ELSONIAN PLUTONS

A rapakivi granite, characterized by the diagnostic plagioclase-mantled potassium feldspars, forms an ovoid pluton west of Voisey Bay. A group of good quality low-uranium zircon from a sample (DL.85.201,L) of this granite defines a discordia line between 1322 ± 1 and 117 Ma. The 1322 Ma age represents the time of crystallization of the zircons, and quite probably the age of emplacement of the pluton.

A sample (US.87.26,M) of similar granite, lacking mantled ovoids, south of Kogaluk River, has yielded an age of 1292 ± 4 Ma, slightly younger than the rapakivi granite above, but still within the time frame of Elsonian intrusions in this part of Labrador.

SUMMARY

The U–Pb geochronology confirms the Archean age for coastal gneisses of the Nain Province, indicates mafic dyke intrusion between 2200 and 2000 Ma, and provides evidence for contact metamorphism ca. 1300 Ma. It has established the Late Archean age of gneisses within the Rae Province and suggests that Early Proterozoic metamorphism, responsible for reworking of the Archean gneisses, reached its peak ca. 1830 to 1800 Ma. However, there is some indication that high-grade metamorphism was also imposed upon parts of this area prior to ca. 1855 Ma. The suite of rocks examined to date indicate that there has been limited growth of zircon in the Archean gneisses of Rae Province during the Lower Proterozoic metamorphic overprint. Elsonian granitoids were emplaced at ca. 1325 to 1290 Ma, apparently generating some new thorite (?) and titanite growth, but at the same time causing significant Pb-loss in zircon. Zircon studies are still being conducted in an attempt to further refine the geological evolution of this area of Labrador.

REFERENCES

Hoffman, P.F.
1988: United plates of America, the birth of a craton: early Proterozoic assembly and growth of Laurentia. Annual Reviews of Earth and Planetary Science, Volume 16, pages 543-603.

Krogh, T.E. and Heaman, L.M.
1989: Report on U–Pb results for the 1988/89 Labrador geochronology contract. Newfoundland Department of Mines and Energy, Geological Survey Branch, unpublished report.

Krogh, T.E. and Oliver, G.
1990: Geochronology report for Newfoundland Department of Mines and Energy. Newfoundland Department of Mines and Energy, Geological Survey Branch, unpublished report, 37 pages. [Lab (14D/40)]

Krogh, T.E. and Schärer, U.
1987: Report on Labrador geochronology. Newfoundland Department of Mines and Energy, Geological Survey Branch, unpublished report.

Ryan, B.
1990: Does the Labrador-Quebec border area of the Rae (Churchill) Province preserve vestiges of an Archean history? Geoscience Canada, Volume 17, pages 255-259.

Ryan, B. and Lee, D.
1986: Gneiss-anorthosite-granite relationships in the Anaktalik Brook–Kogaluk River area (NTS 14D/1,8), Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 79-88.

Ryan B., Lee, D. and Corriveau, L.
1987: Geology of the eastern Churchill Province between Anaktalik Brook and Cabot Lake (NTS 14D/2,6,7), Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 155-159.

Ryan, B., Lee, D. and Dunphy, D.
1988: The discovery of probable Archean rocks within the Labrador arm of the Trans-Hudson Orogen near the Labrador-Quebec border (NTS 14D/3,4,5 and 24A/1,8). *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 88-1, pages 1-14.

Stockwell, C.H.
1982: Proposals for time classification and correlation of Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield, Part 1: a time classification of Precambrian rocks and events. Geological Survey of Canada, Paper 80-19, 135 pages.

NOTE: Geological Survey Branch file numbers are included in square brackets.

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SHADED-RELIEF MAPS OF GEOCHEMICAL DATA TO DELINEATE GEOLOGICAL STRUCTURES

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ABSTRACT

The presentation of geochemical data as shaded-relief images can greatly increase the amount of useful information conveyed, just as can be accomplished with shaded-relief images of topographic and geophysical data. The creation of enhanced images of geochemical data requires the conversion of the point data to a raster format and some preliminary filtering to improve the geochemical signal to noise ratio and the visual appearance of the final image. To perform these initial steps successfully, a thorough understanding of the data's characterisics, both spatial and statistical, is necessary. The effects of applying different filters to the regional lake-sediment data for Newfoundland on the appearance of shaded-relief images is illustrated.

INTRODUCTION

Image-processing of geochemical data provides a powerful technique for clarifying subtle but significant spatial patterns and, in some cases, cryptic features are revealed that were completely hidden in a background of noise. The use of image-processing is familiar to many geologists as applied to satellite imagery and geophysical data. A technique that is widely applied to magnetic survey data is the creation of shaded-relief images to highlight geological structures. Application of the same technique to lake-sediment geochemical data is proving similarly effective in delineating regional structures.

Geochemical surveys that are designed to map element-distribution patterns define chemical surfaces that resemble topographic surfaces or geophysical potential fields (e.g., from aeromagnetic surveys). Structural features that are reflected in these geochemical (or geophysical) surfaces arise from three main geological situations: 1) the juxtaposition of two geological units of contrasting composition (e.g., along an intrusive or faulted contact); 2) alteration along a linear zone (commonly fault-controlled); and 3) the offset of continuous geological units along a fault. The first two give rise to an abrupt change in geochemical level, which in the first situation usually provides merely further confirmation of a known feature, but may also provide new information in the case of mapping hydrothermal alteration zones. Similarly, in the third situation, the geochemical delineation of an obvious, geologically defined fault provides little new insight, but more subtle discontinuities related to basement structure may also be revealed.

Geochemical surfaces are displayed commonly as contour maps (Plate 1) that portray general variations in chemical concentration. Monochrome shaded-relief images (Plate 2) emphasize local, relative variations in geochemical level, whereas colour shaded-relief images (Plate 3) depict both local and overall variations in level and thus present more of the intrinsic information in the geochemical dataset. Both types of shaded-relief image have their uses and other types of image-processing are available for other applications (e.g., anomaly recognition). Most image-processing is based on gridded or raster data, and the initial gridding must be done paying due attention to the data's characteristics. This will ensure that all the relevant information is retained, without the introduction of artifacts during data processing.

DATA PREPARATION

When interpolating geochemical data from an irregularly distributed set of sample sites to a regular grid, it is possible to effect varying degrees of smoothing. For example, if regional trends are the main interest, then data from several nearby sites may be averaged to minimize the effects of local variation and outliers (including anomalies), resulting in a smooth map of broad-scale trends. If anomalous values are the main concern, then as much as possible of the local variation must be retained. The creation of shaded-relief images is but one of several methods of image enhancement possible with geochemical data; filtering techniques for anomaly recognition form another important class. To create a gridded dataset useful for most image-processing techniques, it is efficient to adopt a simple and conservative method of gridding that minimizes smoothing and retains as much detail (including noise) as possible. To this general-purpose gridded dataset, various filters may be applied to produce secondary grid-files for specific applications (anomaly recognition, delineation of regional trends, etc.). The choice of an appropriate approach for the creation of the initial gridded dataset is critical to the success of subsequent data analysis, and depends upon an appreciation of the data's characteristics, both geochemical and spatial. This appreciation is gained through the following steps.

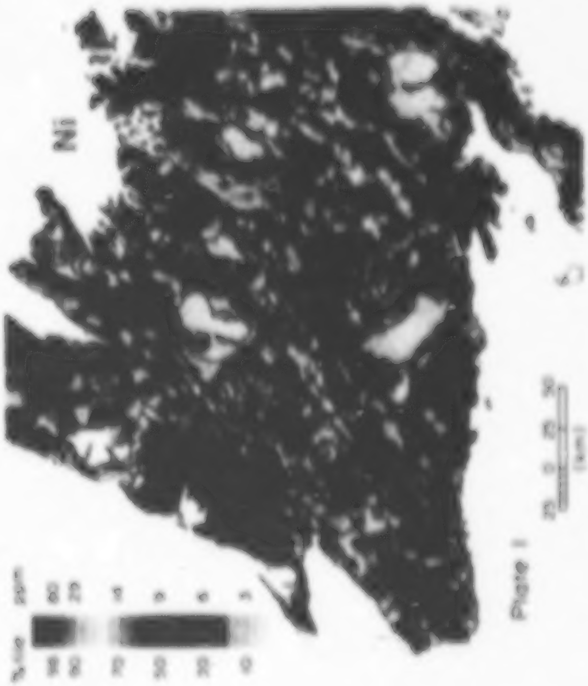
Ni
%ile
ppm
25 0 25 50
(km)

Plate 1

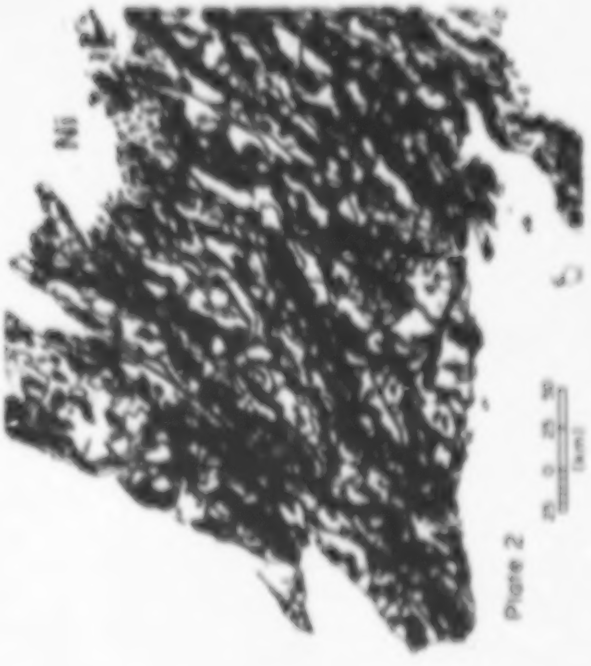
Ni
25 0 25 50
(km)

Plate 2

Ni
%ile
ppm
25 0 25 50
(km)

Plate 3

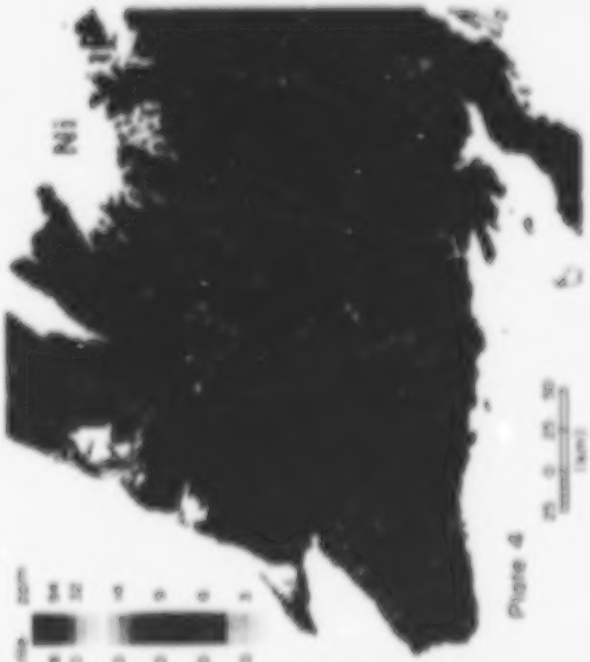
Ni
%ile
ppm
25 0 25 50
(km)

Plate 4

DATA EVALUATION

Examination of Element Frequency Distributions

This is accomplished through the calculation of basic statistics (mean, median, standard deviation, coefficient of variation and range) and probability plots, using a statistical package such as UNISTAT (Nolan, 1990). For elements that are clearly not normally distributed a transformation is recommended. Usually a log transformation is used for trace elements having a high coefficient of variation (>0.5). Outliers and major populations are also identified at this stage. Outliers can be removed, although with the use of robust filters (Chork and Mazzucchelli, 1989) in subsequent processing this may not be required, and in the creation of the initial grid they are usually retained. The identification of any major, distinct populations may aid later interpretation of the enhanced images. Contour levels are chosen from the probability plot, using either the approach of Sinclair (1976) or on a percentile-based scheme.

Evaluation of Data Quality and Sources of Error

Where available, data from site duplicates should be used to obtain an indication of data reproducibility for each element with respect to the overall range of the data through a simple analysis-of-variance approach (Garrett, 1973). If the results are available from more complex, nested-sampling designs (e.g., Garrett and Goss, 1980) that permit variance to be measured at more levels (laboratory, site, sample cell, etc.), this information should be evaluated too, but the most important level is at the sample site.

Examination of the Spatial Distribution of the Data

A custom-written program (GRIDVIEW) is used to determine an appropriate size for the the grid cell in the initial interpolation of the data from the irregularly distributed sample sites to a regular grid. An efficient cell size is one where the proportion of cells containing a single site is a maximum, while the proportions of cells containing either no sites or multiple sites are minima; Chork and Mazzucchelli (1989) note that this type of approach typically results in an average of about 1.5 sites per cell (excluding empty cells). GRIDVIEW allows the cell size to be altered interactively, and calculates a histogram of the number of sites per cell for each cell size chosen. The program also displays the grid and the sample sites on the screen so that the uniformity of the sample coverage can be assessed visually. The data used here in the illustrations have a uniform random distribution, allowing the use of standard random gridding techniques to prepare a gridded dataset. If the sample-site distribution is quite uneven, alternative gridding methods may be required, such as the gap-filling approach of Chork and Cruikshank (1984).

IMAGE CREATION

Initial Gridding

This is carried out on the data, log-transformed as appropriate (see Examination of Element Frequency Distributions section), using a grid-cell size indicated from an examination of the spatial distribution of the data. At this stage as much of the original character of the data as possible is conserved (including noise) by interpolating the value at each grid node from up to four nearest points lying within 2.5 times the length of the grid-cell side, and giving more weight to values from nearer points than more distant points (typically, an inverse of the distance squared is used as the weighting factor).

Initial Image Assessment

Shaded-relief images are created using a custom-written program DISPLAY (Kilfoil, 1990, *this volume*), which permits gridded data to be rapidly displayed on a microcomputer with a VGA monitor. DISPLAY, which adds colour capability to a grey-scale program by Teskey and Broome (1984), offers several options interactively, including: choice of colour or grey shades, inclination and declination of illumination, windowing (through decimation), and the display of two images side by side, with independent display parameters. The image is evaluated subjectively for the clarity with which it shows geochemical features. The image at this stage usually contains a good deal of local variation, which gives it a 'pockmarked' appearance that obscures the more continuous geochemical features (Plate 4). The degree of this

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Plate 1. *Colour contour map of Ni in lake sediment in Newfoundland plotted on a geological framework digitized from Colman-Sadd* et al., *1990.*

Plate 2. *Greytone shaded-relief image of Ni in lake sediment in Newfoundland after filtering using a 3 by 3 cell ATM filter, and two passes of a 3 by 3 cell moving-average-filter, plotted on a geological framework digitized from Colman-Sadd* et al., *1990. Illumination from 315°*

Plate 3. *Colour shaded-relief image of Ni in lake sediment in Newfoundland after filtering using a 3 by 3 cell ATM filter, and two passes of a 3 by 3 cell moving-average-filter (plotted on a geological framework digitized from Colman-Sadd* et al., *1990). Illumination from 315°*

Plate 4. *Colour shaded-relief image of Ni in lake sediment in Newfoundland after initial gridding (no filtering), plotted on a geological framework digitized from Colman-Sadd* et al., *1990. Illumination from 45°*

Ni
% tile
ppm
25 0 25 50
(km)

Plate 5

Ni
% tile
ppm
25 0 25 50
(km)

Plate 6

Au
% tile
ppb
25 0 25 50
(km)

Plate 7

Ni
% tile
ppm
25 0 25 50
(km)

Plate 8

local variation (or noise) varies from element to element and is usually least noticable for elements whose variance at the sample site level is small compared with their overall variance (see Evaluation of Data Quality and Sources of Error section). It also varies with shading direction, and is least noticeable when illumination is perpendicular to the main structural grain (Plate 5).

Smoothing and Filtering

Much of the noise in the images at this stage is a result of the parameters deliberately chosen in the initial gridding (see Initial Gridding section). Several filtering methods to smooth geochemical data have been described. The simplest in concept is a moving average type (Howarth, 1983, chap. 5), using a n x n pixel window that is passed over the data one or more times. The degree of smoothing increases as n increases, and with the number of passes of the filter over the data. Inherent in the moving average filter are assumptions about the frequency distribution of the geochemical data (e.g., that the data are from a normal distribution). These assumptions are seldom tested in practice, and commonly are not satisfied, although in many cases this is more of a concern to statisticians than geologists as the resulting images are geologically useful. However, robust alternatives are available that require fewer and less stringent assumptions to be met, and therefore, provide images that are more acceptable both practically and theoretically. The Median filter and the Adaptive Trimmed Mean (ATM) filter (Chork and Mazzucchelli, 1989) are two such approaches. The Median filter provides a conservative estimate of regional trends, but inherently removes almost all anomalies. The ATM filter affords a robust and effective approach to smoothing regional geochemical data while retaining a good deal of local data variance (including anomalies). To produce a satisfactory image, the window size of the filter is varied and the results displayed and evaluated subjectively. The larger the filter, the greater the area over which the data are generalized and the more the fine detail is lost, so its size depends in part on the degree of generalization required. The results of using a 3 by 3 cell ATM filter (representing a 6 by 6 km window) on Ni are shown in Plate 6. This image is still somewhat grainy and this graininess can be diminished by further smoothing using a simple moving average filter on the log-transformed data (Plate 3). This approach works well even for an element such as Au, where over 80 percent of the values are below the analytical detection limit, and the higher values are noisy (Plate 7). The adaptive trimmed mean program was modified from Rock (1987).

During smoothing, the variance of the data is reduced. Typically, however, there is a proportionally greater reduction in the noise component than the significant geochemical patterns, resulting in a better signal to noise ratio. The random noise tends to cancel, whereas the non-random geochemical signals tend to reinforce. To display subtle features after filtering it, is advantageous to stretch the range of residual values to utilize the full colour range available on the image display system, a feature offered by DISPLAY, and most commercial programs. Final images are best displayed on a monitor having a resolution higher than a VGA screen. The shaded-relief images can be printed by capturing the DISPLAY image using commercial software designed for this purpose. The figures presented here were printed through GEOSOFT, a commercially available, general purpose, mapping system. This permits the data to be plotted at any desired scale with a geochemical legend. The data can be plotted on either a topographic or geological base or both, with shading patterns from one or more directions of illumination.

DISCUSSION

The choice of parameters used to produce shaded-relief images of a geochemical dataset is dictated ultimately by the resolution of the survey itself. The term resolution as applied to a geochemical survey has not been defined clearly, but implicitly it refers to the subtlest geochemical feature that can be detected with some specified degree of confidence. The subtlety could be due to either the size of the feature (in which case sample spacing and the representivity of the sample medium would be the limiting factors on resolution) or its geochemical contrast (where data quality would be the more important factor). Sample spacing is fixed during survey design and is common for all elements, but representivity and quality will vary from element to element (representivity

Plate 5. *Colour shaded-relief image of Ni in lake sediment in Newfoundland after initial gridding (no filtering), plotted on a geological framework digitized from Colman-Sadd et al., 1990. Illumination from 315°*

Plate 6. *Colour shaded-relief image of Ni in lake sediment in Newfoundland after filtering using a 3 by 3 cell ATM filter (plotted on a geological framework digitized from Colman-Sadd et al., 1990). Illumination from 315°*

Plate 7. *Colour shaded-relief image of Au in lake sediment in Newfoundland after filtering using a 3 by 3 cell ATM filter, and one pass of a 3 by 3 cell moving-average-filter (plotted on a geological framework digitized from Colman-Sadd et al., 1990). Illumination from 315°*

Plate 8. *Colour shaded-relief image of Ni in lake sediment in Newfoundland after filtering using a 3 by 3 cell ATM filter, and two passes of a 3 by 3 cell moving-average-filter (plotted on a geological framework digitized from Colman-Sadd et al., 1990). Illumination from 225. Note linear 'A' (the 'Buchans linear') and linear 'B'; both of which crosscut the main northeast-southwest structural grain.*

varying with the mobility of the various elements). Data quality can be measured from site-duplicate samples, and representivity can be estimated in relative terms from a nested sampling design or variograms, but the resolution cannot be exactly quantified because of the size-contrast ambiguity. The resolution of geochemical surveys for a geochemical feature of specified size and contrast is a function of both sample spacing and representivity (Figure 1). Thus, for a given survey, resolution varies from element to element, being a function of the different element representivities, or, to look at it from a different perspective, the resolution of a low-density survey for Ni (one site per 200 to 400 km²) is roughly equivalent to the resolution for Au in a much higher density survey (one site per 7 km²) using the same sample medium (lake sediment). Other elements are intermediate between Ni and Au (e.g., Sb), and a rough guide to the relative order of resolution in a survey is given by the ratios of total-data variance to within-site variance.

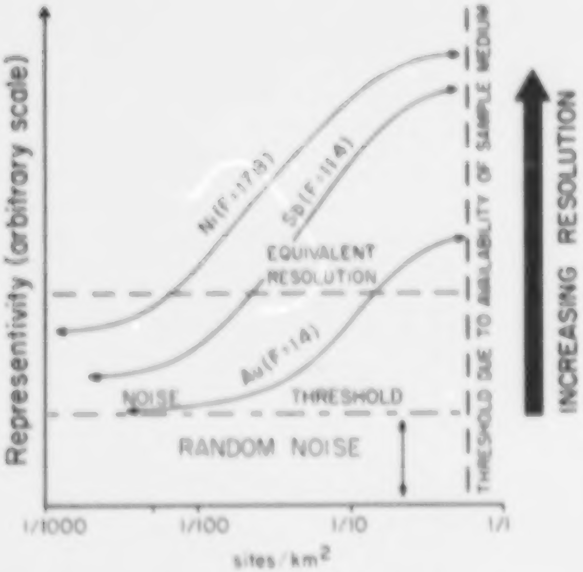

Figure 1. *Schematic depiction of the relationship between sample density and element representivity in lake-sediment data from Newfoundland. Representivity is approximated by the ratio of the total-data variance to the within-site variance (F values).*

A further point, illustrated by Figure 1, is that although an increase in sample-site density will result in an increase in survey resolution, for any particular sample medium there is an optimum range over which this relationship is linear. However, at very high-sample densities further increases in site densities result in smaller and smaller increases in resolution. In the case of lake sediment, sample density is limited by the distribution of lakes, and to increase densities to greater than 1 site per 4 to 5 km², either very small ponds and marshes must be sampled, which commonly yield poor samples with a consequent loss of data quality, or multiple sites must be sampled in the larger lakes, which results in an uneven sample-site distribution. In either case, there is little gain in target resolution. To increase resolution, surveys based on other sample media that are intrinsically capable of providing this higher resolution (e.g., soil) must be employed.

At the other extreme the relationship is less clear, although intuitively it seems likely that meaningful patterns will become indistinguishable from background noise at some very low-sample density. Most successful very low-density surveys employ either special sample media such as overbank stream sediment (Ottesen *et al.*, 1989) or a special sampling technique such as that used in the Geochemical Atlas of Finland (Koljonen *et al.*, 1989).

CONCLUSION

These differences in resolution for the different elements in a survey necessitate a flexible approach for producing images of maximum clarity for each element. Smoothing by filtering should aim for the best signal-to-noise ratio. The portrayal of data as carefully prepared images greatly increases their impact and the amount of useful information conveyed. Although some time and effort must be invested for effective data presentation, the resources needed are minor compared with those expended on sample collection and analysis, and add a great deal to the overall impact of geochemical surveys. The linear features revealed by shaded-relief maps of elements such as Ni not only provide new insight into enigmatic structural features such as the 'Buchan's linear' ('A' in Plate 8), but also reveal others ('B'), which may have important implications for regional geological models and mineral exploration.

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REFERENCES

Chork, C.Y. and Cruikshank, B.I.
1984: Statistical map analysis of regional stream-sediment data from Australia. Journal of Geochemical Exploration, Volume 21, numbers 1-3, pages 405-419.

Chork, C.Y. and Mazzucchelli, R.H.
1989: Spatial filtering of exploration geochemical data using EDA and robust statistics. Journal of Geochemical Exploration, Volume 34, number 3, pages 221-244.

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. (Compilers)
1990: Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-1.

Garrett, R.G.
1973: The determination of sampling and analytical errors in exploration geochemistry—a reply. Economic Geology, Volume 68, pages 282-283.

Garrett, R.G. and Goss, T.I.
1980: The appraisal of survey effectiveness in regional geochemical surveys of Canada's Uranium Reconnaissance Program. Mathematical Geology, Volume 12, pages 443-458.

Howarth, R.J.
1983: Statistics and Data Analysis in Geochemical Prospecting; Handbook of Exploration Geochemistry, Elsevier, 437 pages.

Kilfoil, G.J.
1990: DISPLAY: A computer program for the interactive display of files of gridded data on a VGA monitor—program diskette and user's manual, version 1.0. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File NFLD 2064.

This volume: DISPLAY: An interactive program to create colour images of spatial data on a PC.

Koljonan, T., Gustavsson, N., Novas, P. and Tanskanen, H.
1989: Geochemical Atlas of Finland: preliminary aspects. Journal of Geochemical Exploration, Volume 32, pages 231-242.

Nolan, L.W.
1990: UNISTAT: statistical and graphics package for geochemists. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 129-130.

Ottesen, R.T., Bogen, J., Bolviken, B. and Volden, T.
1989: Overbank sediment: a representative sample medium for regional geochemical mapping. Journal of Geochemical Exploration, Volume 32, pages 257-278.

Rock, N.M.S.
1987: ROBUST: an interactive FORTRAN-77 package for exploratory data analysis using parametric, robust and nonparametric location and scale estimates, data transformations, normality tests, and outlier assessment. Computers in Geoscience, Volume 13, pages 463-494.

Sinclair, A.J.
1976: Applications of probability graphs in mineral exploration. Association of Exploration Geochemists, Special Volume 4, Rexdale, Ontario, 95 pages.

Teskey, D. and Broome, J.
1984: Computer programs for production of shaded relief and stereo shaded relief maps. *In* Current Research, Part B. Geological Survey of Canada, Paper 84-1B, pages 375-389.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 271-277

DISPLAY: AN INTERACTIVE PROGRAM TO CREATE COLOUR IMAGES OF SPATIAL DATA ON A PC

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ABSTRACT

A computer program has been written for the interactive, colour display of gridded datafiles on an IBM-PC (or close compatible) equipped with VGA or better resolution graphics. The program will display gridded datafiles having the storage formats of two popular PC-based gridding and imaging software systems. The gridded datafiles can be displayed as a variety of images on a VGA monitor, in order to extract the maximum information about the grid contents from the data.

In the most basic display mode, 'flat' images (similar to contour maps) are generated by representing the magnitudes of gridded data values by either 64 grey-scale intensities ranging from black to white or as 253 colour hues arranged in the natural order of the visible light spectrum with blues representing low intensities and deep reds representing the high intensities. The other image types that may be generated either in colour or as monochrome displays are shaded-relief, contour levels and shaded-contour levels. A provision to display the natural logarithm of gridded data values was specifically included for geochemical datafiles. Two images created from all or portions of two gridded datafiles may be generated in a split-screen display.

In addition to parameters that control the image type, the display parameters, which may be interactively selected from a simple menu and changed, are: the colour range, the file names, the direction and inclination of shading, the relief factor, and parameters controlling the portion of the grid to be imaged.

INTRODUCTION

During its early days of development, the motivation for writing the program DISPLAY was to provide a tool for rapidly viewing the contents of a gridded datafile as colour shaded-relief images on a desktop computer, and to allow the user the ability to interactively change the direction of false-illumination enhancement. The routine was developed in conjunction with an ongoing project to detect errors in the aeromagnetic profile data available for the province, to generate a contiguous set of gridded datafiles from that data (Kilfoil, *this volume*) and to release the error-corrected gridded datafiles as a digital Open File (Kilfoil and Bruce, 1990). Since many versions of gridded datafiles were generated in the process, the foremost design considerations for the program DISPLAY were speed and versatility in use. Many of the options now available within DISPLAY were added on, to increase versatility after many hours of use. Program DISPLAY was released as an Open File (Kilfoil, 1990) to assist in the interpretation of released gridded digital datafiles.

Although program DISPLAY was designed to generate colour, shaded-relief images from gridded geophysical data, images may be produced from any type of gridded data. For example, the contents of gridded datafiles might be various geochemical datafiles, digital elevation data, soil acidity, population density or forest resource value.

The software will only operate on IBM-compatible microcomputers configured with a combination of a graphics card and colour video monitor of VGA or higher resolution. Although DISPLAY will function with computer display boards of higher than VGA resolution (such as Super VGA), the program is not designed to take full advantage of this increased graphics resolution and its operation will appear as VGA. DISPLAY presently accepts the formats of gridded datafiles as output from GEOSOFT™ Inc.[1] and General Purpose Mapping System or GEOPAK™ Systems[2], two gridding and plotting software packages in common use throughout the geoscientific community in Canada.

In order to obtain the maximum effect of shaded-relief imaging, DISPLAY was designed to take full advantage of the 256 colours available under VGA resolution. However, to achieve the maximum colour resolution, the maximum spatial resolution was degraded to the 320 by 200 resolution from the 480 by 640 resolution available under 16-colour VGA mode. For program efficiency considerations, DISPLAY preforms a one-to-one mapping of grid cells to image pixels. Consequently, the values of only 320 by 200 grid cells can

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[1] (c) Copyright GEOSOFT Inc., Toronto, Canada.

[2] (c) Copyright GEOPAK Systems Software Resources, Toronto, Canada

Table 1. Example parameter menu, from program DISPLAY, used to generate dual images of a single datafile in a split-screen display mode. Note that these parameter settings will generate two grey-tone shaded-relief images from file 'mag_12a.grd': one with false illumination from the northeast, the other from the southeast. Plate 1c is a screen-capture print of the images that result from the parameter settings listed

```
  Parameters are:
      File names:        'mag_12a.grd'               'mag_12a.grd'
   Size (NX,NY):            745,558                     745,558
          Origin:           300,300                     300,300
      Decimation:              1                           1
         Azimuth:             45.0                       135.0
     Inclination:             45.0                        90.0
   Relief factor:           10.00000                    10.00000
      Zmin/Zmax:     -600.0000,  1000.0000      -600.0000,  1000.0000
  Hist equalized:              1                           1
          Colour:              0
        Enhanced:              1
         Shadows:              0
          Levels:              0
 RGB Background:       (45,20,10)   Max=63

 Choose:  'File,Orig,Dec,Azi,Inc,Rel,Z-Ext,His,Col,Enh,Shad,Lev,Back'   (X-Exit)
```

be displayed on the screen at one time. In the split-screen display mode, the display area available for each of the images is 160 by 200 pixels. A previously published grey-scale shading algorithm (Teskey and Broome, 1984) was adapted to the 64 levels of grey, ranging from black to white, available under VGA resolution for grey-tone shaded-relief image generation. The routine was further modified for the production of colour, shaded-relief images from the 256 colours available in a VGA palette. DISPLAY, written and compiled in FORTRAN (Microsoft, 1989), was optimized for the IBM-PC by a library of enhancement subroutines (Sutrasoft, 1989).

During the design of DISPLAY, the objective was to attain the maximum user-friendliness possible for the novice without creating a program that is too slow or cumbersome for the more experienced user. For this reason, and to keep the program trim and efficient, only a few basic image-generating functions have been included. However, the routine does have sufficient versatility that a quite thorough examination of a gridded dataset can be carried out.

For a detailed description of program usage, the reader is referred to the user's manual (Kilfoil, 1990). The description to follow is intended to summarize that document and provide some examples of images that can be created.

INTERACTIVE CONTROL OF DISPLAY AND EXAMPLE IMAGES

DISPLAY uses two screens: a menu screen and an image display screen. The menu lists the parameters (Table 1) that control the generation of images on the display screen. When the menu screen, with the display parameters set as desired, is entered, the image is computed and appears on the display screen. The 'enter' key functions as a toggle between the two screens, allowing the display parameters on the menu screen to be adjusted and the resulting images inspected rapidly until the desired image display is obtained.

A portion of the gridded aeromagnetic datafile for NTS 12A, central Newfoundland (Kilfoil and Bruce, 1990), was chosen as the gridded dataset, from which example images were produced (Plates 1 and 2). This area was selected because a broad range of magnetic field strengths are represented. For reference, the town of Buchans is located just north of centre on each of these prints (a,b,c,d), and the semi-circular magnetic high situated along the northern boundary (just east of centre) is the southward-thrusted margin of the Topsails Complex to the north. Much of the area in the centre and to the southeast is underlain by volcanogenic sediments of the Buchans and Victoria Lake groups.

Plates 1 and 2 are printed copies of captured screen images in grey-level and colour, respectively. The images were generated by a HP Vectra PC on a VGA resolution graphics card and colour monitor, converted to printer plots by the Pizazz Plus (Application Techniques, 1989) image-capturing software, and printed at 1:250,000 scale on a HP Paintjet XL colour printer. Due to the pixel aspect ratio of the 256-colour VGA resolution, all images generated are slightly distorted (stretched in the Y- or north dimension). However, the scaling capability of Pizazz Plus has allowed distortion to be eliminated on Plates 1 and 2. As a result of this screen-capture process, the panels of Plates 1 and 2 are not as crisp as the images generated on the VGA monitor. As well, the colouring on the captured prints tends to be much darker than the on-screen images. The descriptions of menu parameters that

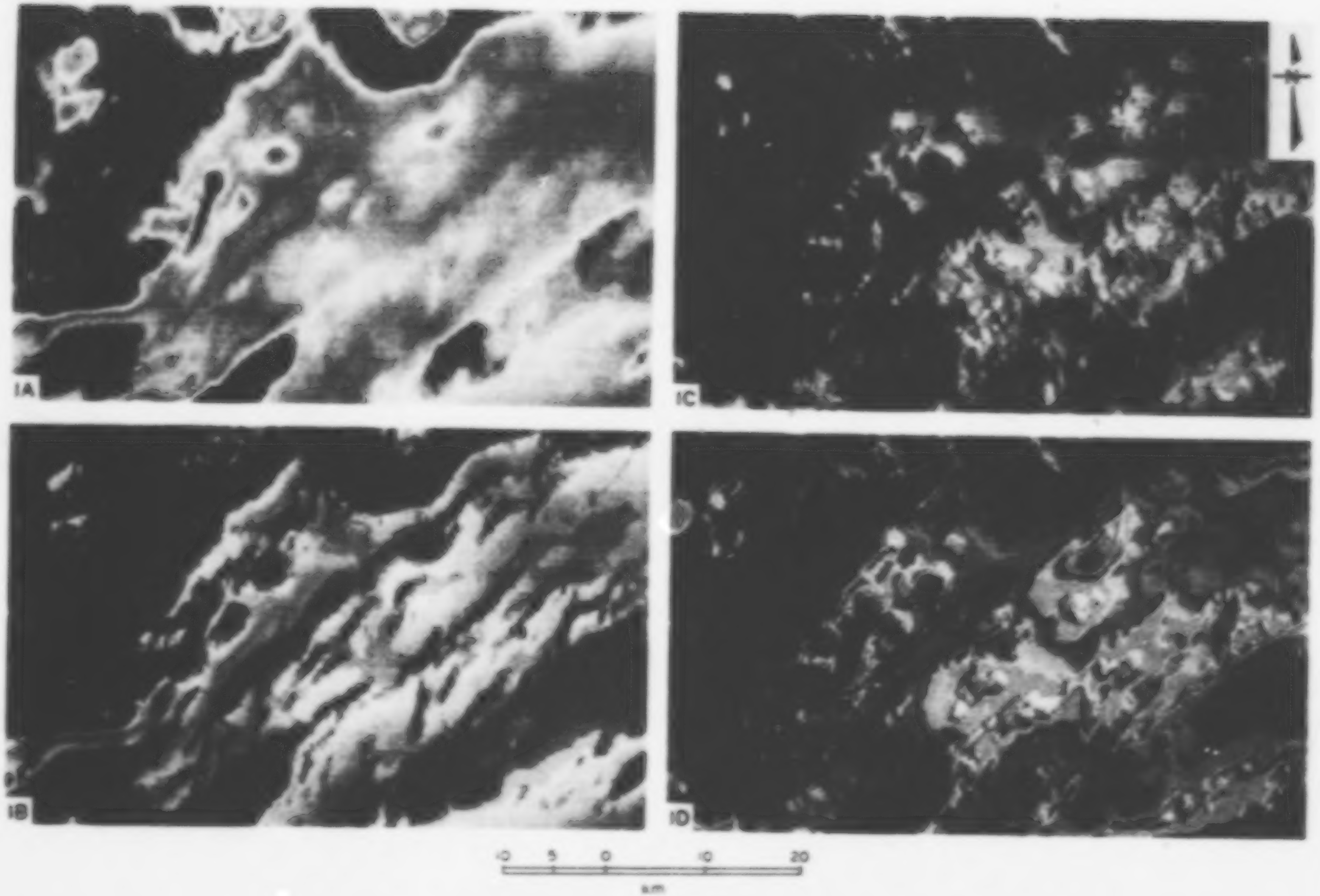

Plate 1. *Prints from various grey-tone images of corrected regional aeromagnetic data, Buchans area, NTS 12A, Nfld. a) 64 grey-level magnetic intensity image; b) shaded-relief image, false illumination from the southeast and inclined at 50°; c) split-screen, shaded-relief images for western half of 1a, image on left half illuminated from northeast at 45° inclination, image on right half illuminated as in 1b; d) shaded-relief, stepped levels image, illumination from the northeast inclined at 45°. Prints captured from a VGA monitor by Pizazz Plus software.*

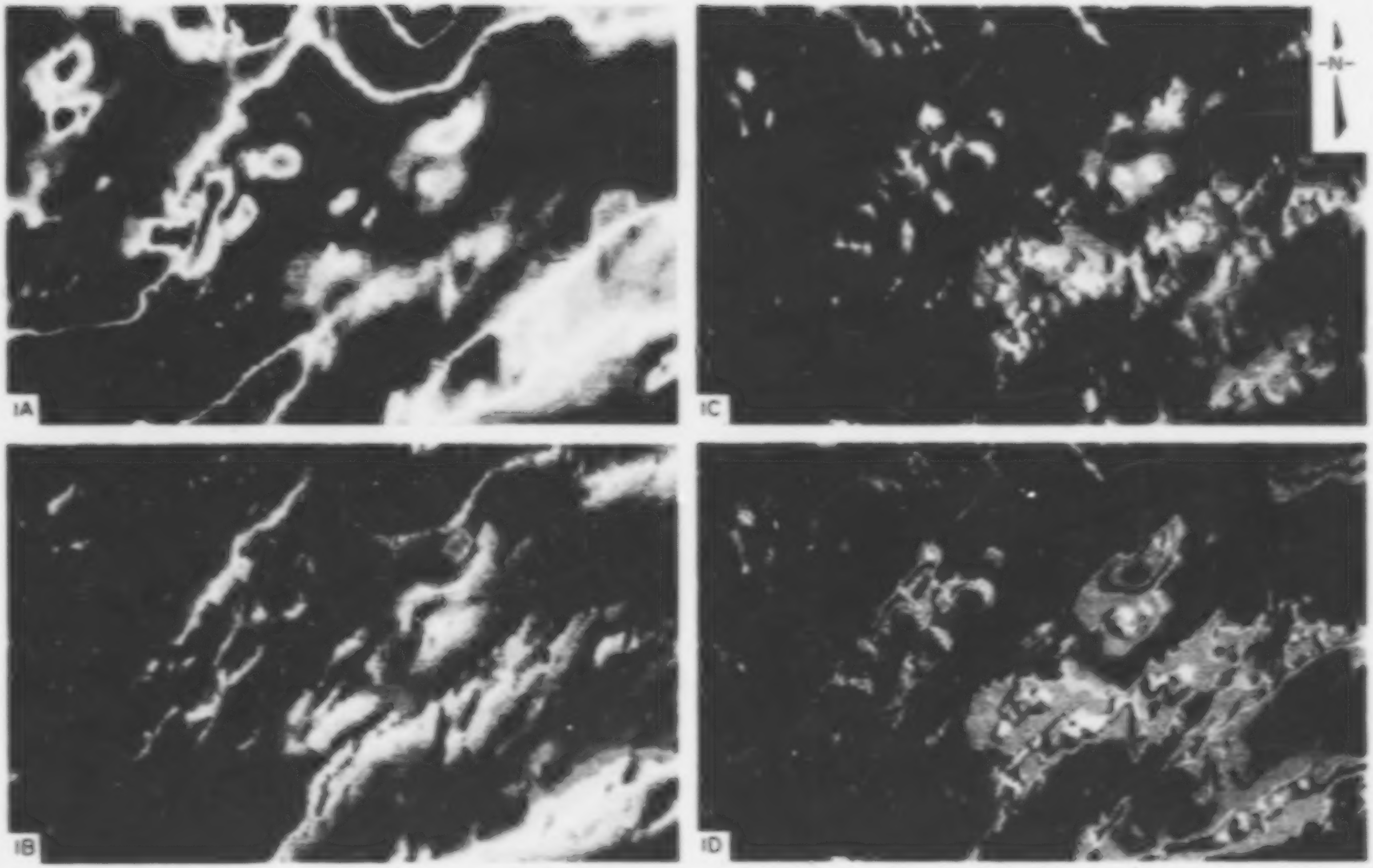

Plate 2. *Prints from various colour images of corrected regional aeromagnetic data, Buchans area, NTS 12A, Nfld. a) 253 rainbow colour magnetic intensity image; b) colour, shaded-relief image, false illumination from the southeast and inclined at 50°; c) colour, shaded-relief image, illuminated from northeast at 45° inclination; d) colour, shaded-relief, stepped levels image, illumination: Azimuth 045°, Inclination 45°. Prints captured from a VGA monitor by Pizazz Plus software.*

follows illustrate, through reference to these examples, the effects of display parameters on images generated.

When program DISPLAY is initiated, the names of a Sun control file and one or two gridded datafiles are included on the DOS command line. The Sun file sets a few initial display parameters so that they need not all be changed from the parameter menu. The contents of the Sun control file are arranged such that the same Sun file may be used to view the contents of all grid files of a specific type, such as aeromagnetic, VLF-EM, etc. The defaults for display parameters that are initialized in the Sun file, are (see descriptions below): image type, Azimuth and Inclination of false illumination, Relief factor, Z_{max}/Z_{min} and control values used by the Levels option.

Four parameters control the type of image to be generated: Colour, Enhanced, Shadows and Levels. Since the various types of images selected involve colour palette changes, two different image types may not be plotted on the screen in the split-screen display mode. Therefore, the values of these menu parameters appear only once in the listing (Table 1), regardless of whether two image files are listed or not. Each of these parameters may be toggled to the 'on' state (1) or 'off' state (0) by typing the first letter. The initial state of each of these parameters is determined by values in the Sun control file (Kilfoil, 1990).

The Colour parameter determines whether a colour or grey-tone image will be generated. The panels of Plate 1 were captured from screen images generated with Colour turned off; those of Plate 2 are prints from images with the Colour parameter activated. Shaded-relief, grey-tone images are often useful for detecting linear features in gridded datafiles, as the observer is not influenced by the colour variations assigned to the absolute magnitudes of grid values.

When the Enhanced parameter is activated the image(s) generated will appear to have apparent relief, resulting from introduction of shadows caused by false illumination. If the Enhanced parameter is off, then grey-tone (Plate 1a) or colour rainbow (Plate 2a) images are generated from the scaled magnitudes of grid values. Shaded-relief images are generated in grey-tone (Plate 1b, c) or colour (Plate 2b, c) when the Enhanced parameter is turned on. Since the Azimuth, Inclination and Relief parameters control the orientation of enhancement, these parameters have no effect when the Enhanced parameter is inactive.

The Shadows parameter determines the emphasis of shadows on the image. When Shadows is turned off, all areas in shadow on a shaded-relief image will be black. With the Shadows parameter activated, half of the intensity range for grey-levels or colours are apportioned to each of the shaded and unshaded regions on the image, thereby allowing some detail to be extracted from areas in shadow. Shadows will have no effect on images when the Enhanced parameter is off. Generally, colour, shaded-relief images are brighter and more appealing when Shadows is on (Plate 2b to d), whereas grey-tone, shaded-relief images are more effective when Shadows is off (Plate 1b to d).

Activating the Levels parameter will map the range of possible grid values onto a series of stepped levels, which resemble the contours of a topographic relief map. The Levels parameter will cause such mapping irrespective of the values of the Colour or Enhanced parameters. The levels onto which the data is mapped and the emphasis or steepness of gradients between levels are determined by variables contained in the Sun control file, and can be edited by the user. Plates 1d and 2d are monotone and colour shaded-relief examples with the Levels parameter activated. As may be observed in these examples, the Levels option can be useful for emphasizing particular trends in the data. Images generated from lake-sediment geochemical data with the Levels command on have also proven useful for comparing gridded data to existing colour contour maps.

When the File-name parameter is selected from the parameter menu, the user is first asked if changes to the number of files to be displayed is desired; then for changes to the File name. Thus, the File-name parameter allows a switch from the single-file display to the dual-file display. The two file names can be changed independently in the split-screen display mode, or the same file name can be typed to obtain a dual image of the same data. The menu of Table 1 shows the menu-parameter listing of a split-screen display of single-gridded datafile. Plate 1c is a print of the image that results from these input parameters. Thus, the data from a single file may be viewed as images from two different illumination directions. Alternatively, using two different Decimation factors (see below), a large gridded datafile may be viewed on one side as an 'index map' (using large Decimation), while the origin of the other image (small Decimation) may be independently changed to view portions of the grid contents in greater detail.

The file Size parameter is included in the menu to provide the user information on the size(s) of any gridded datafile(s) selected, where NX is the number of grid cells (or pixels) per row and NY is the number of rows in the grid. It directly precedes the Origin parameter in the menu for reference when selecting an Origin for display, and is the only parameter in the menu list that cannot be changed. If a file Size of 0,0 appears when a new File name is entered, re-enter the File name before displaying the image.

Two menu parameters, the Origin and Decimation factor, determine the portion of input grid that will occupy the available plotting screen space when an image is generated. The Origin refers to the grid cell that will occupy the lower left pixel in the image window. The number of pixels available on the screen is 320 by 200 for a single-image display, and 160 by 200 for a two-image display. The default Origin, always quoted in grid coordinates, is **1,1** (origin of the grid). Interactive entries are to be integers in the order 'X,Y', referring to grid coordinates. If the entries input by the user are outside the range of possible coordinates for the grid, the grid-coordinate extreme values are taken as default. As example, if **0,0** is entered by the user, then the Origin is set to **1,1**. The X-coordinate of the Origin may be changed, say to 50, while leaving the Y-coordinate unchanged, by entering only **50** or **50,** at the prompt. Similarly, the Y-coordinate may be changed (to 50), by entering **,50**. The position (or absence) of the comma determines which coordinate the user is referring. The image Decimation bears similarity to the scale of a hardcopy plot. It refers to use of every N^{th} grid cell in generating the image, where N is the Decimation factor. That is, if the Decimation factor is set to 2, then only every 2^{nd} grid cell in both the X and Y dimensions will be used to generate the image. The Decimation factor must be an integer greater than zero. By default, the image Decimation is set to **1** unless otherwise entered on the command line. A 'postage-stamp-sized' image of the grid contents can be generated by setting the Decimation factor to a large number, such as **10** or **20**. Compare the Origins with the grid-file Sizes listed in Table 1.

The amount of emphasis on shaded-relief images is controlled by three parameters listed in the menu: Azimuth, Inclination and Relief factor. Initial values for these parameters are taken from the first line of the Sun control file. The Azimuth and Inclination parameters define the angles, in degrees, at which a false illuminating sun is oriented with respect to the topographic representation of gridded data when generating a shaded-relief image. The Azimuth is the direction angle of the false sun, measured clockwise from a **0.0**° value at true North. Thus an Azimuth of **90.0**° is east; a west Azimuth can be obtained as **270.0**° or **-90.0**°. The Inclination defines the angle of the false sun or illuminating vector above the horizon, increasing with angle from *zero* at the horizon. An Inclination of **90.0**° defines a false sun source located directly 'above' the image (or from the viewer's perspective). Note that with the Inclination set to **90.0**°, the image will remain unchanged irrespective of the Azimuth setting. The best settings for Inclination, when using shading as a directional filter to enhance subtle structure in a gridded dataset, are in the range **30** to **60** degrees (above the horizon). The area in shadow on images increases with a decrease in sun angle. Therefore, the Inclination can be lowered to enhance particular trends, but only at the expense of overall loss of detail on the image. When the Azimuth of false illumination is perpendicular to the predominant grain of an image, as in Plates 1B and 2B, the Inclination should be increased slightly to de-emphasize the grain (Inclination parameter increased to **50.0** in listing on the right, Table 1).

The Relief factor refers to a scaling used to adjust the relative 'height' of the grid values when generating a shaded-relief image, and therefore determines the 'roughness' of the image. The initial setting should be in the range of the average difference in Z-values between adjacent valid grid cells. As a rough guide for choosing a Relief factor, divide the range of the Z-values (Z_{max} minus Z_{min}) by 200. When displaying most aeromagnetic datafiles gridded to 200 m, a good colour-shaded image is generated with a Relief factor of about **10** (Table 1). Increasing the Relief factor decreases the image roughness when shading, and vice-versa. If shaded images appear 'flat', decrease the Relief factor, initially by an order of magnitude, and observe the difference in the displayed image. If a shaded image is too rough or 'noisy', increase the Relief factor. By adjusting the Relief factor and the false sun Inclination, an image can quite quickly be obtained, which optimally displays the features of interest in the gridded datafile.

The Z-extremes refer to the minimum and maximum Z-values to which the field values of the valid grid cells will be *linearly* stretched when assigning a representative colour scheme during creation of an image. Z_{min} and Z_{max} are really the extremes of a linear colour spectrum: grid Z-values near (or less than) Z_{min} will be assigned the deepest blue colour, whereas Z-values near (or greater than) Z_{max} will be assigned the deepest red colour; all other Z-values will be linearly stretched when assigning respective colours between these two extremes. This option is merely a means of allowing the user to alter the image colour scheme to locally emphasize a particular feature of interest. These values may be entirely different from the true extremes of actual values in the grid. The initial values of Z_{min} and Z_{max} are obtained from the second line of the Sun control file. The value of Z_{max} should exceed that of Z_{min}; if Z_{min} is greater than Z_{max}, the values are exchanged. The Z-extreme value settings will have no effect on images generated, *if* the Histogram equalization option is enabled.

The Histogram parameter controls linearizing or stretching of the Histogram of grid values when generating an image such that the colour values available for display (which represent field strengths in the grid) should occur in the image with nearly equal frequency. More simply stated, this option should assign equal weighting to each possible display colour in the image, and therefore produce the maximum dynamic range in the image colour scheme. If present, the histogram of grid values, from which the Histogram equalization is calculated, is written to the header of a GEOSOFT™ Version II format grid; the Histogram is appended as a footer line in GEOSOFT™ Version I and Geopak™ gridded datafiles. A value of **1** means 'on' or 'active', while a **0** means 'off' or 'inactive' and therefore a default to linear colour scaling between Z_{min} and Z_{max}. If Histogram equalization is available (Histogram has been included) for a particular grid, then selecting this option will toggle between **0** and **1**. Plate 1a and all panels of Plate 2 were generated with Histogram equalized grey-tone or colour scaling.

The RGB Background refers to a series of three integer values, within the range 0-63, in the order: (Red, Green, Blue), that define the Background colour value *for grey-tone images only*. This option was added to allow choice of any aesthetic Background hue, which contrasts best with the grey-tone image(s) generated. The medium grey (value: 32,32,32) tone used as Background for colour images (which cannot be altered) would obviously not be a good choice for grey-scale images. The currently active value of the Background colour appears between brackets in the menu (Table 1). The default is (**45,20,10**), a reddish-brown colour. As examples, a deep blue would be (**0,0,63**); a deep green: (**0,63,0**); an aquamarine: (**0,63,63**); white (**63,63,63**), etc.

The other option, not listed in the parameter menu, that is available with DISPLAY is the ability to generate images from logarithmically scaled grid values. However, this option can only be activated by selecting the appropriate image type in the Sun control file (for details, see Kilfoil, 1990).

LIMITATIONS

As mentioned above, DISPLAY was not intended to be a fully fledged image-analysis system. At present, images can only be displayed on a VGA colour monitor; RGA graphics capabilities do not have sufficient colour resolution to do justice to a colour, shaded-relief image. The ability to overlay vector files, such as digital topographic data or digitized geology, has not yet been included, but future versions may well include this feature, as the lack of an image-referencing capability is the most obvious drawback to DISPLAY at present.

DISPLAY has been designed for optimal performance on IBM-PC's equipped with a math co-processor. The routine can be implemented on PC's that do not have a co-processor, but the floating-point calculations required for image colour scaling and shading significantly slow its speed of image generation.

The Histogram equalized colour option may only be available with GEOSOFT™ Version II grid formats because there is insufficient space in the grid headers of other grid formats to store a histogram of grid values. However, DISPLAY does accept a frequency histogram appended as a footer record to GEOSOFT™ Version I and Geopak™ format grids. The presence on the frequency histogram is indicated by the setting of a flag in the header of these grids formats. If a histogram of grid values has not been added to the grid, DISPLAY will revert to linear colour scaling. The ability to calculate a histogram of grid values on-line would be of benefit; however, this function should be optional as it would carry a high price in computer processing time.

At present, GEOSOFT™ or Geopak™ are the only grid-file formats that DISPLAY will accept. However, if the demands warrant, support for other grid-file formats may be added to future releases of DISPLAY. Although hardcopy support has not been incorporated into DISPLAY to date, support for certain colour printers in common use would be preferable to the screen capture utility used to print the images contained herein.

Program DISPLAY requires a Sun control file, which must be specified on the command line. This requirement could be eliminated if DISPLAY were programmed to inspect the contents of a each grid file and make 'intelligent guesses' at initial values to use in their display. To date, this option has not been implemented as the computation time required would slow the operation of DISPLAY considerably.

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REFERENCES

Application Techniques
1989: Pizzaz Plus, User's Guide and software for the IBM-PC. Application Techniques, Inc., Pepperell, Massachusetts, USA, 132 pages.

Kilfoil, G.J.
1990: DISPLAY–a computer program for the interactive display of files of gridded data on a VGA monitor, computer program (Version 1.0) & User's Manual. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File NFLD (2064), 24 pages.

This volume: Breathing new life into old data: colour images from the corrected, regional aeromagnetic dataset for insular Newfoundland.

Kilfoil, G.J. and Bruce, P.A.
1990: Regional aeromagnetic data grids (200 m grid cell), in digital form, for all of insular Newfoundland, Version 1.0. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File NFLD (2063), 24 pages.

Microsoft
1989: Microsoft FORTRAN Reference Manual and Optimizing Compiler, Version 5.0. Microsoft Corporation, Redmond, Washington, USA, 523 pages.

Sutrasoft
1989: FORTLIB, FORTRAN Enhancement Library for Personal Computers, User's Manual, Version 4.00. Sutrasoft (The Librarian, Inc.), Sugar Land, Texas, USA, 205 pages.

Teskey, D. and Broome, J.
1984: Computer programs for production of shaded relief and stereo shaded relief maps. *In* Current Research, Part B. Geological Survey of Canada, Paper 84-1B, pages 375-389.

Current Research (1991) Newfoundland Department of Mines and Energy
Geological Survey Branch, Report 91-1, pages 279-288

BREATHING NEW LIFE INTO OLD DATA: COLOUR IMAGES FROM THE CORRECTED, REGIONAL AEROMAGNETIC DATASET FOR INSULAR NEWFOUNDLAND

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ABSTRACT

Regional aeromagnetic data for insular Newfoundland have been corrected and levelled and are now available by NTS map area, as a series of digital Open Files, at a grid-cell interval of 200 m. The data are released as individual grids, for each 1:250,000-scale NTS map area, in order to accommodate their easy storage and retrieval, as well as to maximize data access speed. Gridded datafiles for adjacent NTS map areas may be joined successively to generate a single grid for all of insular Newfoundland. The gridded dataset is available in two commonly used grid-storage formats. A conversion utility is provided to allow any portion of the data to be output to a text file.

INTRODUCTION

Data from regional potential-field surveys have historically been presented as contour maps, from which, either features have been interpreted by correlation with surface geological information or profiles have been extracted as input to various types of quantitative modelling techniques. With the common use of the personal computer (PC) during the 1980's, image-processing techniques have been applied with increasing frequency to extract textural information, as well as to enhance the more subtle but often large-scale linear features contained in these data. Increasingly, the published literature contains examples of subtle, linear features (on the scales of a country (cf. Lee *et al.*, 1990) to a continent cf. O'Driscoll, 1986), identified from gravity and aeromagnetic data, which have been correlated with megascopic structural trends and related to the locations of major-ore deposits.

In order to extract subtle spatial features from aeromagnetic data through image analysis and enhancement techniques, the data must first be relatively error free and interpolated to a regular grid. Many of the various types of errors that may exist in the data, may be of sufficient magnitude to overshadow or at least distort the geometry of the subtle magnetic expression of important structural features. The methods for identification and correction of the many errors and inconsistencies that exist in the digitized profiles, which comprise the regional aeromagnetic dataset, have been previously discussed (Kilfoil, 1990a). Although the reader will be briefly updated as to any changes to the processing sequence, the objective of this report is to present a portion of the data as colour, shaded-relief plots and to show, through these examples, how subtle features in the corrected aeromagnetic dataset may be interpreted.

This project was undertaken to provide a corrected and levelled aeromagnetic dataset for the Island of Newfoundland, as a series of levelled digital data grids for 1:250,000-scale NTS map areas, which can be joined to form a seamless, contiguous grid for the whole of the province. The project was initiated because of the strong interest, both within and outside the Newfoundland Department of Mines and Energy, to acquire quality-gridded geophysical data. The gridded datafiles that result are particularly designed for input to image analysis and display systems.

The first phase of the project involved correction of positional errors, contour–flight-line intersection labelling errors, and the digitizing of flight-line segments omitted from the data. Flight-line segments from adjoining map sheets were then merged interactively on a PC to reconstruct, as closely as possible, the original recorded database. Inter-survey levelling errors were then effected and the corrected profile data were gridded to a 200-m grid interval. The grid-cell size was selected to retain as much as possible of the detailed information, while at the same time making the overall gridded dataset no larger than necessary. Much of the levelling error that exists between adjacent flight lines was efficiently removed by subsequent application of wavenumber domain filtering. Finally, smaller gridded datafiles were joined to yield a single, corrected and levelled grid for insular Newfoundland. The entire dataset is presented as a colour map in Plate 1. At the scale used to plot this plate, the outlines of major bodies of water, geological contacts and faults added in increasing respective line weights for reference, mask much of the local detail in the dataset. However, Plate 1 is useful for correlating regional zones and trends in the aeromagnetic data with the geology from surface mapping.

The gridded dataset for insular Newfoundland was subdivided into a series of individual gridded datafiles of manageable size by extracting only the grid cells that lie within each 1:250,000-scale NTS map area. The entire dataset

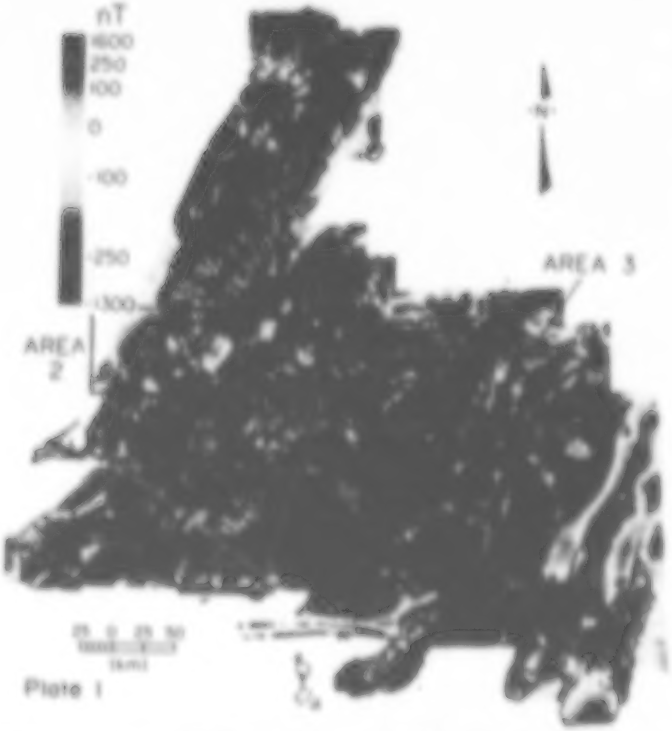


Plate 1

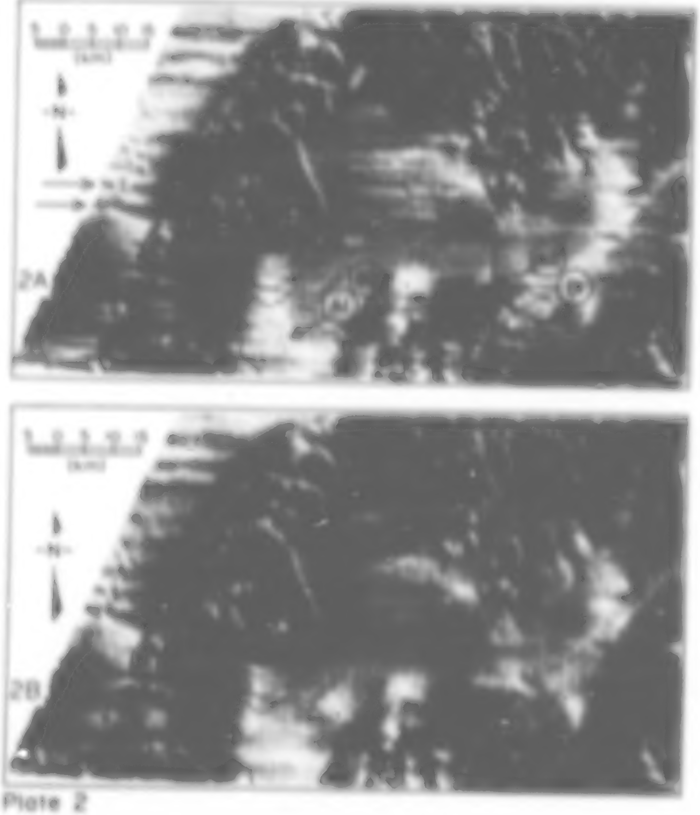


Plate 2

or any of the component datafiles are available on floppy diskette at nominal cost, in the grid formats of two PC-based software systems in common use: GEOSOFT™ Inc. and GEOPAK™ Systems (Kilfoil and Bruce, 1990). Alternatively, the contents of a gridded datafile can be dumped to an ASCII file for input to other systems. This basic corrected, levelled and gridded version of the standard Geological Survey of Canada aeromagnetic data can be very rapidly and easily re-gridded on a PC to any interval size that meets the user's objectives. Similar processing is underway on the aeromagnetic dataset for Labrador.

JOINING FLIGHT-LINE PROFILE SEGMENTS

Aeromagnetic data for Newfoundland were originally collected by the Geological Survey of Canada (GSC) in four major surveys, flown between 1953 and 1971 (Kilfoil, 1990a, Figure 1, survey blocks 1 to 4). The data, collected by analog methods at 300 m (1000 ft) altitude along generally east-oriented flight-lines spaced at 0.8 km (0.5 miles), were transcribed to 1:63,360 (1"=1 mile) paper plots and hand-contoured. During the 1980's, the data were captured in digital form by digitizing the points along each flight line of the intersection of contours on these paper contour maps of the province. In July 1988, these digital aeromagnetic data, covering the whole of Newfoundland and Labrador, were received (Geological Survey of Canada, 1988).

Plate 1. *Colour map of levelled and corrected GSC aeromagnetic anomaly data for insular Newfoundland. Black lines, in order of increasing line weights, trace the coastline, geological contacts and major faults (from Colman-Sadd et al., 1990), respectively. The colour spectrum is linearized by the histogram of magnetic anomaly values to give equal distribution throughout the map (note values along scale bar). Locations for Plates 2 and 3 are outlined in white and are denoted as Areas 2 and 3, respectively.*

Plate 2. *Colour, shaded-relief maps of regional aeromagnetic data for parts of NTS 12G and 12H, western Newfoundland, a) before and b) after data editing and removal of flight-line levelling error. Black line is digital coastline extracted for reference from EMR Surveys and Mapping Branch's vector topographic data. Shading is created by introduction of a false light source from the northeast, inclined at 45° to the horizon. Marked features are discussed in the text.*

Upon initial attempts at gridding, filtering and displaying the data as images, several types of errors became apparent in the data. Digital images derived from uncorrected digitized profile data exhibit distinct features that result from: levelling errors that exist at boundaries between different survey blocks, discontinuities along individual map-sheet boundaries within survey blocks incorrectly labelled contour intersections, and the levelling errors among adjacent flight-line profiles. In addition, the quality of the digitized product was found to vary somewhat with the survey area. An interactive computer program, MAPJOIN, was written to join and effect corrections to the data from individual map plots as a means of restructuring the dataset within individual survey blocks.

CORRECTING DIGITIZING ERRORS

A comprehensive description of the digitized aeromagnetic profile data and a rigorous account of the digitizing-error correction procedure applied to the flight-line profiles are contained in Kilfoil (1990a). Most of the digitizing errors located along map boundaries were corrected during the profile joining process. However, many of the errors located within map sheets, such as mis-labelled contour intersections, still remained. Considerable effort has been expended in locating and correcting these errors.

The effects that digitizing errors may have on gridded datasets, and the images produced from them, is illustrated by Plate 2, which are a pair of images produced from a portion of the gridded data for NTS map areas 12G and 12H. Plate 2a is a colour, shaded-relief image (false illumination from the northeast) of the gridded datafile produced from uncorrected aeromagnetic profiles. Plate 2b is the equivalent image derived from profile data after correcting for digitizing and flight-line levelling error. For the purpose of referencing these images, the thin black line that traces the coastline near the Bay of Islands, was extracted from 1:250,000-scale digital topographic data (Energy, Mines and Resources, 1990) and added to these plots. The roughly circular features having high-magnetic relief (reds) located in the west-central region of these images, are an expression of the more magnetic units within the Bay of Island ophiolite complexes. The locally variable magnetic field, giving these features a mottled texture on Plate 2, is characteristic of the occurrence of variable magnetic rocks in outcrop or at shallow depth.

The north-oriented features marked by 'A1' and 'A2' on Plate 2a are expressions of the discontinuities that may occur at the boundaries of adjacent 1:50,000-scale map boundaries before the profile merging process. This type of error is usually the result of improper registration during the data digitizing stage and can be remedied by applying a least-squares stretching to profile positional data within each distorted map sheet (see Kilfoil, 1990a). The westernmost of the errors, marked by 'A1' on Plate 2a, locates the boundary between map areas NTS 12G and 12H, and the upper halves of these images are the colour equivalents to the profile line drawings (Kilfoil, 1990a, Figure 2). The error at this boundary is less prominent on these images than the map boundary to the east (feature 'A2') due to lesser enhancement from the northeast illumination direction. The feature marked by 'A2' is more prominent in the lower half of Plate 2a, where the error located along the boundary between NTS 12H/4 and NTS 12H/3 map areas is particulary well enhanced. Note that these apparent seams caused by discontinuities along map boundaries have been virtually eliminated in the image of Plate 2b.

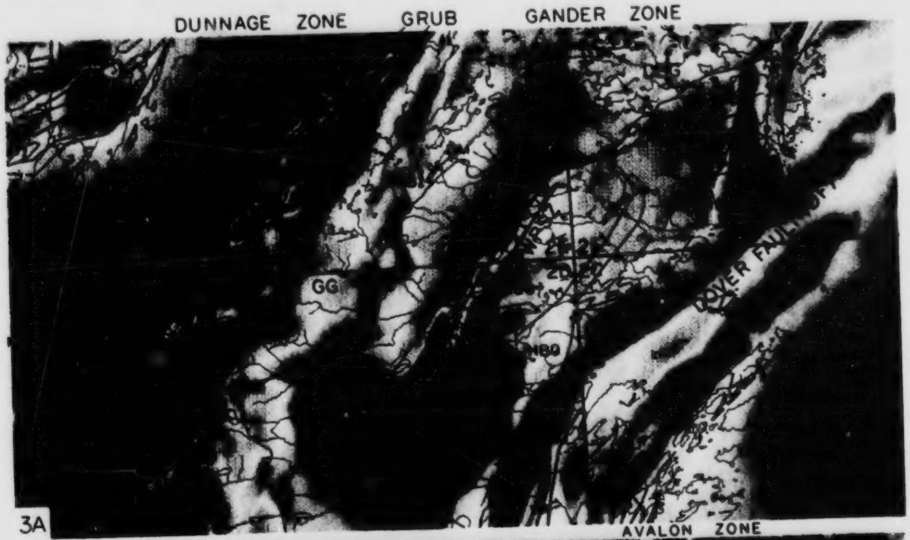
Mis-labelled contour intersections along profiles located within map sheets are expressed as anomalous features in gridded data, such as those indicated by 'B1' and 'B2' on Plate 2a. If several consecutive contour intersections are mis-labelled along a single digitized flight profile, these errors are easily detected on shaded-relief images as relative highs (bumps) or lows (troughs) elongated in the profile direction. The feature marked by 'B1' on Plate 2a provides an excellent example; here, five consecutive contour intersections were assigned magnetic values that were low by 100 nT, creating a suspiciously anomalous trough. The trough marked by 'B2' resulted from three low-contour label assignments along an east-oriented profile. Single, mis-labelled contour intersections are expressed as point anomalies in the gridded data. Although isolated occurrences of mis-labelled contours are more common in the digitized data, they are much more difficult to detect than errors spanning several contours, particularly when located within a region of highly variable magnetic field strength (such as near the northern margins of the images on Plate 2).

The digitizing errors that result from mis-labelled contours were especially prevalent in areas where a variable magnetic field occurred near contour map boundaries. Near map boundaries, these contour levels are not always clearly labelled on the original paper-copy plots. Errors of this type were readily detected during the profile end-point matching process of the merging phase or, following subsequent gridding, as isolated discontinuities along map boundaries on images derived from the gridded files.

The more obvious errors resulting from incorrect contour assignment were easily detected and remedied. However, the more subtle errors that result from only minor contour mis-labelling or from minor positional errors may still exist in the data as these are not readily distinguishable from genuine magnetic anomalies.

PRE-GRIDDING DATA PREPARATION

The procedure employed in survey-block levelling to create a contiguous gridded dataset for Newfoundland has previously been described in detail (Kilfoil, 1990a; Kilfoil and Bruce, 1990). To summarize, data within older survey blocks were corrected by adding differential offsets of magnitudes defined by least-squares polynomials, (Gangi and Shapiro, 1977) which were fitted to offsets along survey boundaries. The aeromagnetic profile data for NTS map areas 12B, 12A, 2D and 2C (Kilfoil, 1990a, survey blocks 1 and 3 of Figure 1) were levelled to the data for surrounding survey blocks by this method. The efficiency of the method is attested to by the continuity of the magnetic field across survey-block boundaries. Plate 3 (to be discussed in more detail later),


DUNNAGE ZONE
GRUB
GANDER ZONE
GG
NBG
DOVER FAULT
AVALON ZONE

3A

3B

3C

provides a representative example of the results from survey block levelling.

The final step in preparing the profile data for gridding involved removal of the Definitive Geomagnetic Reference Field (DGRF) (Regan, 1983) and conversion of the positional data to the Universal Transverse Mercator (UTM) projection (Snyder, 1982; McDonnell, 1979), referenced to the Clarke 1866 geodetic ellipsoid. Profiles of total-field aeromagnetic data are reduced to magnetic anomaly values by reference to the DGRF, the values of which can be calculated at each unique geographic location by interpolation from a series of published (Barraclough, 1988) spherical harmonic coefficients that reflect both spatial and temporal changes in the reference field. Since most of insular Newfoundland is situated in UTM Zone 21 (54° to 60°W longitude), the profile data situated within UTM Zone 22 (comprised largely of the Avalon Peninsula) was converted to Zone 21 before gridding to maintain continuity with only minimal distortion (McDonnell, 1979).

GRIDDING AND POST-PROCESSING

Gridding refers to the transformation of irregularly spaced, spatially referenced data onto a two-dimensional matrix or grid, of uniform spacing in each of the X and Y dimensions. Individual elements comprising the grid are referred to as grid cells or, if the grid is converted to a visual image, pixels. A grid is usually produced by some form of weighted averaging of the data when data points are randomly distributed, or by a line or surface interpolation in the case of data organized into profiles (such as the aeromagnetic data). Interpolating data to a regular grid is advantageous in terms of the ease and speed in which later computation-intensive operations (such as contouring, filtering, plotting) can be applied. Of particular importance is the ease of application of digital filters. The organizational similarity of data in a regular matrix to pixels referenced on a computer monitor enables images to be very efficiently generated from gridded datasets.

DESCRIPTION OF GRIDDING PARAMETERS

All gridded datafiles were generated by the GEOSOFT™ routine, BIGRID, which takes advantage of the organized format of profile data to efficiently interpolate gridded data (Geosoft Inc., 1989a). Following several experiments with grid-cell intervals and discussions of the results, an interval of 200 m was chosen as the best balance between that which contains nearly all of the detail contained in the digitized profile data (even in regions of high magnetic variability) and considerations of data storage and access efficiency. The density of contours in the digitized profile data limits the resolution attainable and ultimately restricts the possible uses of the data. In order to ensure that adjacent grids would be continuous, the grid extremes were chosen as those which expand the areal extent of each grid to that with an approximate 10 percent margin beyond the boundaries of each 1:250,000-scale NTS map area.

As the name suggests, BIGRID is a bi-directional interpolation routine, which interpolates profile data by first interpolating values equispaced (at grid-cell interval) along the flight-line direction, then interpolates the grid-cell nodes between adjacent profiles from these values. Bi-directional interpolation of data organized into profiles is much more efficient than any random gridding, which must sort the data and search the immediate vicinity of each grid cell for neighbouring data points. The user can select the interpolation technique for either of the two directions independently, as linear, cubic spline (Forsythe *et al.*, 1977) or minimum curvature (or akima) (Akima, 1972; Briggs, 1974; Swain, 1976).

The aeromagnetic data grids were created by an initial cubic spline oriented along data profiles, followed by akima interpolation applied in the cross-profile (south to north) direction. This combination was found to be the most effective as the cubic spline preserved detail and ensured smoothness of the digitized data in the profile direction, while the minimum curvature eliminated unwanted 'bumps' in the cross-profile direction, where much less detail was present and subsequent flight-line levelling error removal was planned. An example of the effects of different gridding schemes is shown in Plate 2. The gridded data from which Panel 2a as derived, was created from uncorrected profile data using BIGRID with the along-profile interpolation method set to linear. Note the small irregularities that result, situated near the centre of Plate 2a, in a region of otherwise featureless magnetic field. These subtle irregularities were eliminated by the spline interpolation used to produce the final gridded datafiles (Plate 2b).

Plate 3. *Corrected and filtered GSC aeromagnetic data for portions of NTS map areas 2D, 2C, 2E and 2F, (location on Plate 1) presented as a) standard colour intensity map, b) colour, shaded-relief map; false illumination from azimuth 135°, nclination 45°, and c) colour, shaded-relief map; false illumination from azimuth 45°, inclination 40°. In increasingly heavier ine-weights, the solid black lines trace selected digital topography (lakes, streams and coastline from 1:250,000-scale EMR atafiles), geological contacts, faults and map area boundaries. Geological features marked in a) are: BG—Botwood Group; RF—Bloody Reach Fault; DBG—Deadman's Bay Granite; DPS—Dildo Pond Stock; DF—Dover Fault; GG—Gander Group; RUB—Gander River Ultrabasic Belt; HBG—Hare Bay Gneiss; MBG—Middle Brook Granite; MPIC—Mount Peyton igneous omplex; MRG—Middle Ridge Granite; NG—Newport Granite; RBI—regional biotite isograd (dashed line in NTS map area E); TL—topographic lineament; UM—ultramafic outcrop; WPSZ—Wing Pond shear zone. Outlines of geological features were ligitized from the regional geological map of insular Newfoundland (Colman-Sadd* et al., *1990) and, locally, selected from 1:50,000-scale maps (O'Neill, 1987, 1990). Features are discussed in the text.*

The GSC advocates use of a minimum curvature surface-fitting routine (Akima, 1974) for interpolating a smooth surface through unequally spaced data values. However, bi-directional gridding is much more efficiently applied to profile data and very closely approximates minimum curvature surface-fitting, where the gridding interval relative to profile spacing is small.

The other gridding parameters that were fine-tuned to specific areas were the minimum and maximum interpolation distances and the parameter, NEX, which controls interpolation of N cells extending beyond the end of data profiles. NEX was set to zero for most NTS map areas; the exceptions were NTS 12B and 12P, where profiles extend only to the shoreline or barely overlap. For these map areas, NEX was set at 1 to ensure complete grid coverage. The minimum and maximum gridding distances refer to the extremes of interpolation between profiles; values from profiles that are closer than the minimum distance are averaged whereas cross-line interpolation is not carried out between profiles whose separation exceeds the maximum distance, resulting in a data gap in the grid. The minimum and maximum interpolation distances were set to 100 m and 2500 m, respectively, for most NTS areas. The exceptions to this were NTS 12B and the southeast-oriented flight profiles in NTS 12P, which bridge the Newfoundland data with that for Labrador; in both cases, the maximum gridding distance was increased to 3500 m to avoid gaps in these grids.

REMOVAL OF FLIGHT-LINE LEVELLING ERROR

A final processing step was taken to correct the aeromagnetic database by removing any systematic error that existed in the data subsequent to gridding, the largest source of which is the relative level shifts between adjacent flight lines (Kilfoil, 1990a). Removal of this error is commonly referred to as decorrugation filtering. Much of the flight-line levelling error was determined by first transforming data grids to the spatial frequency or wavenumber domain using a computationally efficient Fast Fourier Transform (FFT), applying digital filtering techniques, then transforming the result back to the spatial domain. All FFT transforms and filtering operations were performed by the GEOSOFT™ Magmap software package (Geosoft Inc., 1989b).

Filtering was accomplished by applying a combination of Butterworth and directional filters (Kulhànek, 1976) tuned to the consistent orientation and the regularity of average line spacing of the original aeromagnetic survey. An 8th order Butterworth filter, with a central wavenumber corresponding to four times the 0.8-km average flight-line spacing, was found to be the most effective in isolating the levelling error without sacrificing the detail contained in the aeromagnetic data. Directional filters were designed to take advantage of the average east-west flight-line orientation. The outputs from the wavenumber filtering stage were gridded datafiles, the contents of which consisted largely of the aeromagnetic flight-line levelling error. The actual correction was applied by subtracting the levelling error grid from the original grid to yield a corrected grid.

The panels of Plate 2 illustrate the effectiveness of decorrugation filtering on the aeromagnetic data grids for NTS map areas 12G and 12H. The east-oriented features due to flight-line levelling error (indicated by arrows on Plate 2a) have been virtually eliminated in the corrected version of Plate 2b. The levelling error filtering and removal causes some smoothing locally in the cross-profile direction, particularly in areas where features are oriented along the flight-profile direction and are of wavelengths comparable with flight-line spacing. Although filtering parameters were selected conservatively in order to keep smoothing of detail to a minimum (note that some apparent east-west corrugation remains evident in Plate 2b), unfortunately some detail may be lost in certain areas and should be considered when interpreting filtered grids. The removal of flight-line noise significantly improves the appearance and continuity of features on images produced from the gridded data. One should bear in mind, during interpretation, the anisotropy in detail caused both by directional filtering and the much denser data detail along flight lines than that (limited by the flight-line spacing) in the cross-line direction.

FINAL GRID PREPARATION

Once the digitally filtered aeromagnetic data grids for Newfoundland were created in piecemeal form, the data required some cleanup and reformatting before it was deemed acceptable for release. The following sections describe the final steps taken to cleanup the data for release.

GRID TRIMMING

As noted above, in order to ensure continuity of data across adjacent gridded datafiles, all data that lie within a margin that surrounds each NTS map area are included during gridding. After filtering, each gridded datafile extended beyond its NTS map boundaries. For the purpose of referencing, the grids were then trimmed by first nulling out all grid cells whose coordinates did not lie within the respective NTS map sheets, and eliminating any null columns or rows, which were marginal to the grids to reduce grid file-size. As a result, each grid value in the entire gridded dataset for Newfoundland was represented only once; that is, no grid cell appears in both of two adjacent grid files. A routine designed to join spatially referenced grids, program MERGEO, was written to provide clients the ability to merge gridded datafiles from adjacent NTS areas.

INCLUDING A HISTOGRAM

In order that the user better understand the distribution of data contained within the gridded dataset, a frequency histogram of grid values was incorporated into each aeromagnetic data grid. The histogram consists of 32 integers representing the numbers of non-null grid cells with magnetic values that fall within 32 intervals. The 32 intervals are equispaced between the grid minimum and maximum Z-values, two parameters that are normally stored in the grid headers.

Since the grid header of GEOSOFT™ Version II grids is 512 bytes in length (GEOSOFT, 1989c), there is plenty of previously unused space in which to store the 128 bytes required for the histogram. However, the 128-byte total size of Geopak™ and GEOSOFT™ Version I grid headers make it impractical to store the histogram; instead a flag is set in the header, which indicates the presence of a 128-byte histogram appended as a footer to these grid types. When present in a gridded datafile, the histogram is used by the program DISPLAY (Kilfoil, *this volume*) to calculate histogram equalized colour scaling during image generation. Note that if later processing, such as filtering or data transfer operations, is performed on these grids, there is no guarantee that the histogram will be transferred to the newly created grids or that the histogram will be representative of the distribution of new grid values.

AVAILABLE GRID FORMATS

The gridded datafiles comprising this release are available in two storage formats: GEOSOFT™ or GEOPAK™. GEOSOFT™ has two storage formats: a pre-July 1989 (Version I) sequential access binary file and an updated (Version II) random access binary file. All three formats share a common style, consisting of a single header record, containing the grid dimensions and other descriptor variables, followed by lines of gridded data scaled to the available range of 2-byte signed integers. The gridded, aeromagnetic datafiles are stored as grid lines arranged in increasing X (west to east) within lines and are sequential in Y (south to north) within the grid. Thus, the first grid value stored corresponds to the southwestern-most grid cell.

Header lengths are 512 bytes for GEOSOFT™ Version II gridded datafiles and 128 bytes for GEOSOFT™ Version I and GEOPAK™ files. Thus, GEOPAK™ grids differ from GEOSOFT™ Version I grids only by the descriptor variables and their arrangement as contained in the respective grid headers. Should these formats be found to be incompatible with the user's software, a program is provided that will dump the contents of a binary gridded datafile to an ASCII character file, irrespective of the gridded datafile format purchased. The data are available in either of two IBM-compatible diskette formats: 5-1/4 inch, 1.2 Mb or 3-1/2 inch, 1.4 Mb diskettes.

ADDING SHADED RELIEF TO ENHANCE AEROMAGNETIC COLOUR IMAGES—AN EXAMPLE

The addition of shaded relief to colour images is not only useful for locating errors in a gridded geophysical dataset, but can be a very powerful tool for interpretation of the corrected data. Plate 3 consists of three printed images from the merged aeromagnetic dataset for NTS map areas 2D, 2C, 2E and 2F. This plate is included to illustrate how false illumination can be applied to a portion of the gridded aeromagnetic dataset for insular Newfoundland to enhance the features of interest. Here, the area near Gander was chosen because it represents an area of active geological and geophysical investigations that encompass data from three survey blocks. In regard to the latter, note the continuity of the aeromagnetic features in the data across the NTS map area boundaries, in particular those situated astride the NTS 2D/2E and NTS 2D/2C boundaries. The area encompassed by Plate 2 contains some of the highest and the lowest magnetic anomaly values found in the gridded data for insular Newfoundland.

The light-weight black lines on all three panels of Plate 3 are the outlines of rivers, lakes and coastlines drawn from digital vector files derived from computer-scanned, 1:250,000-scale topographic maps (Energy, Mines and Resources, 1990). The outlines of the major geological contacts and faults, in increasingly heavier respective line-weights, were digitized from the 1:1,000,000-scale geological map of Newfoundland (Colman-Sadd *et al.*, 1990), with the exception of certain local geological units digitized from 1:50,000-scale maps of NTS 2D/15, 2D/16 and 2E/1 (O'Neill, 1987, 1990). The dashed line within the Gander Group (GG) of map area NTS 2E/1 traces the biotite isograd. Dashed lines were also added to trace the offshore continuation of the Dover and Long Reach faults. The heaviest line-weights were used to trace the outlines of the NTS map areas. The colour scheme for this plate is a rainbow arrangement of 37 colours ranging from deep blue for magnetic lows to deep red for high magnetic anomalies. The magnetic anomaly range for each colour was determined by linearizing the histogram of magnetic values from the gridded dataset for all Newfoundland (used to generate Plate 1).

The colour panel of Plate 3a exemplifies a typical 'flat' colour magnetic map. Many of the magnetic features on this map closely correlate with major geological boundaries. Examples are the characteristically non-magnetic Davidsville Group (DG) sediments; the distinctly magnetic ultramafic units within the Gander River Ultrabasic Belt (GRUB); and the magnetic high associated with outcrop of the Newport Granite (NG). Other geological units do not show such a strong correlation to magnetic field strength alone; examples are the Gander Lake Granite (GLG), the Mount Peyton intrusive complex (MPIC) and the Deadman's Bay Granite (DBG). The magnetic expression of certain geological units, such as the Dildo Pond Stock, would suggest that these units are more extensive at depth than indicated by the area of surface outcrop mapped.

The colour panels 3b and 3c of Plate 3 are colour, shaded-relief versions of the aeromagnetic data in panel 3a. The colour scheme used is identical to that used to print panel 3a but grey shadows have been added to the images of panels 3b and 3c by false illumination from the northeast and southeast, respectively. When compared to the colour map of panel 3a, the most striking features on these lower two panels are the linear and curvilinear patterns created by magnetic anomaly gradients, which are differentially enhanced by the shading. When properly chosen, two orthogonal directions of illumination are sufficient for identifying most of the subtle features in an aeromagnetic dataset (Lee *et al.*, 1990).

The northeast shading direction of Plate 3b gives maximum emphasis to any of these features that strike approximately southeast (perpendicular to the false illumination). The southwestern mapped boundary of the DBG and the northeastern boundary of the MPIC, approximately coincide with magnetic features that are particularly enhanced on this panel. A roughly circular magnetic feature located within the DBG (just west of the NTS 2E/2F map boundary) is also enhanced by this illumination. This relative magnetic high is probably an expression of a later, more mafic phase of granite intrusion. Two north-northwest oriented magnetic linears, which obliquely intersect the GRUB, are enhanced in the region between the Middle Ridge Granite (MRG) and the GLG near the southern border of this map. The orientation of these linears at an oblique angle to the northeast structural grain and their situation in proximity to the granitic intrusions would suggest that these two granites may be locally fault bounded. It is noteworthy that all features, even subtle linear magnetic features that trend northeast-southwest, are given a sense of relief in Plate 3b (compare with Plate 3a) by the false illumination from 045°.

In contrast to Plate 3b, all northeast-oriented magnetic features are brought out by the southeast illumination on Plate 3c. Such linear features as the Bloody Reach and Dover faults correspond to prominent magnetic linears, as are several of the minor faulted contacts associated with the GRUB. Several of the intrusive contacts are expressed by curvilinear magnetic patterns, particularly the southeast contacts of the DBG and the MPIC. A subtle, magnetic linear is situated within the Ordovician volcanic-rich sediments of the DG, near the southwest corner of Plate 3c. The orientation of this linear, parallel to the bedding of sediments within the DG, and the fact that the linear pinches out to the northeast suggests that it results from a slightly more magnetic mafic volcanic unit within the sediment package.

Of particular note on Plate 3c are several subtle, sub-parallel northeast-oriented linears (between arrows), which can be traced across the entire north-south extent of the map area, over 70 km in length. These linears are continuous north-northeastward to the intersection with the trace of the GRUB just off the map to the north. The sharpness of these features would suggest that they arise from sources near the surface. The westernmost linear, located just east of Weir's Pond, coincides with a mapped topographic lineament in which highly strained rocks are locally exposed (Goodwin and O'Neill, *this volume*). Several small granitic bodies have been identified in outcrop in the region just east of the linears (O'Neill, 1987); these may be the exposed portions of a larger granitic body at depth.

The fact that at least one of these linears can be traced through the GLG, a posttectonic granite of probable Devonian age, and their straightness suggests that they are due to steeply dipping to vertical faults or mega-fractures along which final movement postdates most tectonic elements in the area. The linears correlate with a region of higher magnetic relief of the Gander Group pelites, semipelites and psammites, which may be at least locally related to higher metamorphic gradient, as shown by the biotite isograd in NTS area 2E. However, on the scale of the Gander Lake Subzone, there is not a consistent relationship with high-grade metamorphic rocks. The magnetic anomalies associated with the Wing Pond shear zone (WPSZ) in the Gander Group do not exhibit such a clearly defined linear magnetic expression. Although situated a few kilometres to the east of the trace of these aeromagnetic linears, a lenticular body of ultramafic rocks (UM) identified in outcrop (O'Neill, 1987) gives credence to the notion that the linears are indicating the presence of faults in the area.

On the basis of the above discussion, these magnetic linears indicated by arrows on Plate 3c are interpreted as due to steeply dipping faults. If such extensive faulting exists within the Gander Subzone, implies that the Gander Group may be structurally repeated across the width of exposure. The origin of the linears are the subject of ongoing investigations in the area.

CONCLUSIONS

The application of shaded relief to gridded potential field data has proven very useful for enhancing subtle trends and features that would otherwise be overlooked in the data. Of equal importance, however, the production of colour, shaded-relief images from the gridded aeromagnetic datafiles has provided an invaluable means for the identification of the systematic and nonsystematic errors that were present in the digitized profile data. The ability to interactively vary the shading direction for colour image enhancement on a personal computer (Kilfoil, 1990b, *this volume*) has expedited the error identification and correction phase.

The rigorous correction of digitizing errors in the profile data and subsequent removal of the systematic flight-line levelling errors through digital filtering have eliminated many of the inconsistencies in the data that could mistakenly be interpreted as real magnetic features. The error corrections followed by levelling applied along the aeromagnetic survey-block boundaries has resulted in a relatively error-free and seamless, gridded aeromagnetic dataset for insular Newfoundland. The continuity of magnetic features across magnetic survey-block boundaries and the identification of very subtle magnetic linears on colour, shaded-relief images created from the dataset attest to its quality.

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REFERENCES

Akima, H.
1972: Interpolation and smooth curve fitting based on local procedures. Communications of the Association for Computing Machinery, Volume 15, number 10, pages 914-918.

1974: Bivariate interpolation and smooth surface fitting based on local procedures. Communications of the Association for Computing Machinery, Volume 17, number 1, pages 26-30.

Baraclough, D.R.
1988: International Geomagnetic Reference Field Revision 1987, International Association of Geomagnetism and Aeronomy Division I, Working Group 1. Geophysics, Volume 53, number 4, pages 576-578.

Briggs, I.C.
1974: Machine contouring using minimum curvature. Geophysics, Volume 39, number 1, pages 39-48.

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. (Compilers)
1990: Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch. Map 90-01.

Energy, Mines and Resources
1990: Digital Vector Topographic Data, on 9-Track Magnetic Storage Tape, scanned from 1:250,000 topographic maps, all areas of the Province of Newfoundland and Labrador (by NTS map area).

Forsythe, G.E., Malcolm, M.A. and Moler, C.B.
1977: Computer Methods for Mathematical Computations. Prentice-Hall, Inglewood Cliffs, New Jersey, USA, 259 pages.

Gangi, A.F. and Shapiro, J.N.
1977: Computer program—a propagating algorithm for determining Nth-order polynomial least-squares fits. Geophysics, Volume 42, number 6, pages 1265-1276.

Geological Survey of Canada
1988: Digital Aeromagnetic Data, on 9-Track Magnetic Storage Tape, for all onshore areas of the Province of Newfoundland and Labrador (by NTS map area).

Geosoft Inc.
1989a: BIGRID: Bi-directional gridding for line data (User's Manual). GEOSOFT™ Inc., Toronto, Canada, 39 pages.

1989b: Magmap Processing System: General purpose 2-D frequency domain processing for potential field data (User's Manual). GEOSOFT™ Inc., Toronto, Canada, 27 pages.

1989c: The Geosoft 2-D mapping system, Appendix B: GEOSOFT Grid File Format, GEOSOFT™ Inc., Toronto, Canada, 5 pages.

Goodwin, L.B. and O'Neill, P.P.
This volume: The structural evolution of the northern segment of the Dunnage Zone–Gander Zone boundary, Newfoundland.

Kulhànek, O.
1976: Introduction to Digital Filtering in Geophysics. Elsevier Scientific Publishing Co., New York, U.S.A., 168 pages.

Kilfoil, G.J.
1990a: From analog aeromagentic contour maps to enhanced colour images: getting the most from an existing potential field dataset. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 107-113.

1990b: DISPLAY—a computer program for the interactive display of files of gridded data on a VGA monitor, computer program (Version 1.0) & User's Manual. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File NFLD (2064), 24 pages.

This volume: DISPLAY: an interactive program to create colour images of spatial data on a PC.

Kilfoil, G.J. and Bruce, P.A.
1990: Regional aeromagnetic data grids (200 m grid cell), in digital form, for all of insular Newfoundland, Version 1.0. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File NFLD (2063), 24 pages.

Lee, M.K., Pharaoh, T.C. and Soper, N.J.
1990: Structural trends in central Britain from images of gravity and aeromagnetic fields. Journal of the Geological Society, London, Volume 147, pages 241-258.

McDonnell, Jr., P.W.
1979: Introduction to Map Projections. Marcel Dekker Inc., New York, pages 122-128.

O'Driscoll, E.S.T.
1986: Observations of the lineament-ore relation. Philosophical Transactions of the Royal Society, London, Volume A 317, pages 195-218.

O'Neill, P.P.
1987: Geology of the Weir's Pond map area (2E/13), Newfoundland. Scale 1:50,000. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 87-84.

1990: Geology of the Gander (east half) and Gambo (west half) map areas (2D/15 & 2D/16), Newfoundland. Scale 1:50,000. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-122.

Regan, R.D.
1983: The current status of the IGRF and its relation to magnetic surveys. Geophysics, Volume 48, number 7, pages 997-998.

Snyder, J.P.
1982: Map projections used by the U.S. Geological Survey. U.S. Geological Survey Bulletin 1532, Washington, D.C., pages 63-72.

Swain, C.J.
1976: A FORTRAN IV program for interpolating irregularly spaced data using the difference equations for minimum curvature. Computers and Geosciences, Volume 1, pages 231-240.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 289-299

SELECTING SIEVE FRACTIONS AND SAMPLE PREPARATIONS TO ENHANCE OVERBANK- AND STREAM-SEDIMENT SURVEYS

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ABSTRACT

Samples of active stream sediment and overbank sediment were collected from part of NTS map area 1M, on the south coast of Newfoundland. During sieving, a variety of mesh sizes were used, and two methods of sample preparation were used for the overbank-sediment analyses. The samples were analyzed for 39 elements. In general, element data from the fine (<63 μm) fractions of both sediment types were found to be more useful than the element data derived from fractions that include coarser material. Element concentration levels and analytical precision are usually higher in the fine fraction, thus yielding data that have improved signal-to-noise ratios. Element data that are most enhanced in the fine fraction of overbank sediment include Ag, Au, Br, Cd, Ce, Cu, Hf, Pb, Sm, Ta and U. Elements that are most enhanced in the fine fraction of active stream sediment include As, Au, Br, Ce, Cu, Hf, La, Ni, Sm, Ta, Tb, U and Yb.

Exceptions to the general trend include Cr, for which the coarse fraction of overbank sediment seems to yield better data, and Mo and W, for which the coarser fraction of active sediment yields better data.

A sample preparation procedure of oxidizing overbank sediment with 30 percent H_2O_2 solution to break down organic aggregations prior to sieving, enhances the signal-to-noise ratio for most data in comparison with data from conventionally prepared samples.

INTRODUCTION AND OBJECTIVE

Commonly, samples from stream-sediment surveys are dried, sieved to <180 μm (<80 mesh) and sent off to a laboratory for analysis. This study suggests that depending upon which elements are of primary interest, the choice of sieve size and sample preparation technique can have a substantial effect on the resulting data. The proper selection can enable the geochemist to tailor the survey to better achieve its goals. In some cases, it may be desirable to split samples and prepare them by more than one method to produce the best information for different element groups.

In this study, samples of overbank sediment and active stream sediment were collected from part of NTS map area 1M on the south coast of Newfoundland (Figure 1). Overbank sediment is normally a fine-grained sediment that deposits as a veneer on the banks adjacent to a stream or river during flooding. An overbank profile reveals the accumulation from many such events. It has been demonstrated in Scandinavia to offer some advantages over conventional active stream sediment as a sample medium (Ottesen *et al.*, 1989), in that, it is more representative of the entire catchment basin and less influenced by industrial and agricultural activity. Two sieve-size fractions were analyzed from both types of samples and two sample preparation techniques were applied to splits of some of the overbank sediment samples. The results are presented and discussed.

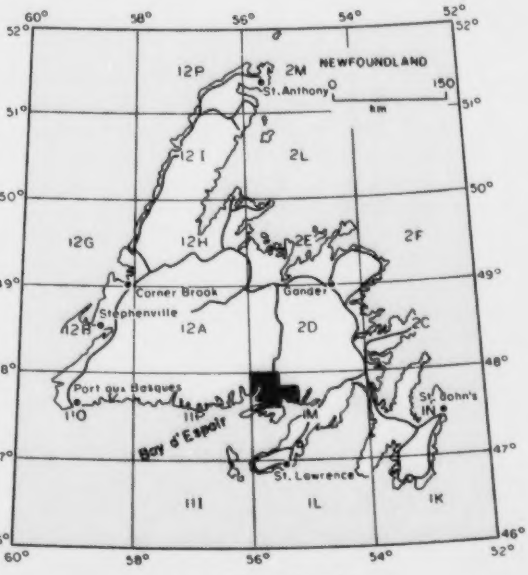


Figure 1. *Location of study area.*

REGIONAL GEOLOGY AND GEOCHEMISTRY

Mapping by O'Brien *et al.* (1981), shows that the northeast-trending Hermitage Bay Fault divides the region into predominantly volcanic, sedimentary and intrusive rocks of Late Proterozoic age to the southeast of the fault (Avalon Zone), and a region of predominantly clastic sedimentary and volcanic rocks northwest of the fault (Gander and Dunnage zones). Numerous mineral occurrences are known from the 1M map area; in particular, map area 1M/13 has over 100 occurrences of Ag, As, Au, Cu, Mo, Pb, Sb and Zn (Brewer and O'Driscoll, 1986).

Regional-scale lake-sediment samples were collected as part of the province-wide lake-sediment survey. A recent publication provides selected element-distribution maps and statistical interpretation for 33 elements, including loss-on-ignition (Davenport *et al.*, 1990). Anomalously high concentrations in lake sediment of Au, Ag, As, Ba, Cr, Cu, F, Mo, Ni, Pb, Sb, W and Zn were indicated.

METHODS OF SAMPLE COLLECTION, PREPARATION AND ANALYSES

SAMPLE COLLECTION

Wherever possible, paired samples of overbank sediment and active stream sediment were collected from adjacent sites to compare the geochemical responses of the two materials. Seventy-one samples of active sediment and 63 samples of overbank sediment were collected. Duplicate overbank and active sediment samples (site duplicates) were collected at twelve sites. A duplicate overbank sample is a second sample collected at a suitable site within about 100 m of the first. Duplicate samples of active sediment were collected from approximately the same areas of the stream bed.

A sample of overbank sediment was obtained by digging a small pit to expose the overbank profile, which normally ranged from 15 to 50 cm in thickness. A representative sample of the section was then collected from the face in a fashion similar to obtaining a channel sample in bedrock. Active stream sediment was sampled from several sources in the stream bed using a spade. About 10 to 15 L of <5 mm sediment were obtained initially by screening material through a garden sieve. This was further reduced to <300 μm by wet-sieving on-site, resulting in a final sample weight of about 200 to 300 g.

SIEVING, SAMPLE PREPARATION AND ANALYSES

All overbank samples were first oven-dried and sieved and the <500 μm fraction retained. When microscopic examination of the samples indicated that many grains were actually composites of smaller grains, thirteen of the larger samples were split and an additional sample series created. In an attempt to disaggregate the composite grains, the following procedure designed to oxidize the binding organic matter was performed on samples of this subseries.

Approximately 100 to 200 g of sample were placed in a beaker and saturated with distilled water. A solution of 30 percent H_2O_2 was gradually added while stirring the sample until effervescence ceased. The mixture was heated slowly to about 70°C and evaporated to dryness. The sediment was then wet-sieved with distilled water into two size fractions, <63 and 63 to 500 μm.

The procedure for the other split portion of the subseries, as well as for all remaining overbank samples, consisted of soaking the samples overnight in a very weak (3 percent) solution of H_2O_2 and wet-sieving them into two size fractions as above.

The samples of <300 μm active sediment were dry-sieved to form two fractions, <63 and <180 μm. No additional sample preparation was performed.

The various size fractions and sample series described above were analyzed by a variety of methods for forty elements. Some elements, notably Ba, Ce, Co, Fe, La, Ni, Sc and Zn were analyzed by more than one method. Of the elements discussed in this report, As, Au, Cr, Mo, Sb, Ta and W were determined by neutron activation analysis and Ag, Mn and Pb by atomic absorption analysis. As a check on accuracy and precision, a standard sample of known composition and a sample duplicate (split) were included in each batch of 20 samples. Details of analytical methods may be found in McConnell and Honarvar (1991).

RESULTS

SIZE FRACTIONS

Distribution Statistics

One method of assessing the impact of analyzing different size fractions is to compare basic statistics of the element populations. Tables 1 and 2 list the geometric means, $\log_{10}$ standard deviations and data ranges of most of the elements analyzed. To permit comparisons between the two sample types, data have been included only from the 49 sites that have both overbank- and active stream-sediment samples. The data have been log-transformed to compensate for the positively skewed distributions of these elements. Most have standard deviation/mean ratios >0.5 in the untransformed data.

From Table 1, the mean values of the fine fraction of overbank samples equal or exceed the mean values of the coarse fraction for most elements. Exceptions, e.g., where the mean value in the coarse fraction is significantly greater than in the fine fraction, include Ba, Cr, Rb and Th by ICP analysis.

Comparing the mean values of the <63 and the <180 μm fractions of active sediment in Table 2 indicates that the tendency toward enrichment of trace elements in the fine fraction is even more pronounced in this type of sample. Of all elements analyzed only Ba, Mo and Rb and the major element Na have higher mean concentrations in the coarser fraction.

Table 1. Means, standard deviations and data ranges of <63 μm and 63 to 500 μm fractions of overbank sediment. Means and ranges in g/t unless otherwise specified (N=49)

	GEOMETRIC MEAN		STANDARD DEVIATION (log)		DATA RANGE	
	<63 μm	63 - 500 μm	<63 μm	63 - 500 μm	<63 μm	63 - 500 μm
Ag	0.11	0.05	0.34	0.15	0.05– 0.5	0.05– 0.4
As	29.50	26.30	0.56	0.58	2.4– 402	1.7– 473
Au (mg/t)	1.66	1.29	0.41	0.29	1– 24	1– 15
Ba	363.00	407.00	0.21	0.22	99– 1237	89– 1286
Ba1*	324.00	372.00	0.36	0.37	25– 1400	25– 1400
Br	34.70	21.90	0.43	0.43	2.2– 300	1.7– 216
Cd	0.25	0.15	0.30	0.32	0.1– 2	0.1– 1.4
Ce	72.40	57.50	0.23	0.21	20– 501	19– 312
Ce1	75.90	55.00	0.25	0.31	26– 564	5– 360
Co	12.10	12.90	0.44	0.45	1– 287	1– 339
Co1	12.30	12.90	0.48	0.50	2– 330	2– 420
Cr	58.10	100.00	0.37	0.29	10– 310	10– 390
Cs	7.08	6.17	0.16	0.16	2.8– 18	1.3– 13
Cu	16.20	12.30	0.38	0.40	1– 134	1– 67
Dy	4.47	3.89	0.24	0.24	1.6– 21.8	1.2– 16.3
Eu	0.72	0.74	0.25	0.24	0.5– 6	0.5– 3.5
Fe (%)	2.82	3.02	0.19	0.21	0.54– 7.78	0.67– 9.48
Fe1 (%)	3.89	3.55	0.17	0.19	0.81– 8.6	1.5– 10
Ga	21.90	21.40	0.09	0.11	12– 33	10– 33
Hf	7.59	4.37	0.22	0.16	2– 20	1.8– 14
La	30.90	25.10	0.26	0.22	8– 305	8– 171
La1	29.50	22.90	0.28	0.23	5– 297	6– 140
Li	35.50	36.30	0.19	0.20	13.2– 88.4	10– 81.5
Lu	0.22	0.17	0.34	0.34	0.1– 1.6	0.1– 1.3
Mn	692.00	741.00	0.53	0.50	104–13300	90–12370
Mo	3.02	2.69	0.57	0.47	0.5– 35	0.5– 23
Na (%)	1.05	1.10	0.13	0.17	0.4– 1.7	0.34– 2.18
Nb	9.33	8.13	0.24	0.22	2– 57	2– 39
Ni	15.10	13.50	0.39	0.47	1– 81	1– 69
Ni1	10.20	12.90	0.41	0.44	5– 99	5– 79
Pb	22.40	14.80	0.32	0.35	7– 192	3– 132
Rb	77.60	91.20	0.21	0.18	19– 230	27– 250
Sb	1.02	0.98	0.42	0.45	0.15– 8.5	0.19– 6.4
Sc	10.20	9.55	0.14	0.19	3.5– 19	2.3– 18
Sm	6.46	5.01	0.27	0.23	1.3– 52	1.4– 30.2
Sr	89.10	87.10	0.20	0.22	19– 230	20– 212
Ta	1.17	0.91	0.26	0.27	0.2– 7.2	0.2– 5.2
Tb	1.02	0.81	0.30	0.26	0.2– 5.3	0.2– 4.6
Th2	3.72	6.31	0.60	0.40	0.5– 55	0.5– 41
Th1	10.23	8.13	0.24	0.21	4.3– 52.4	3.6– 35.3
U	5.13	3.72	0.36	0.34	1.7– 73.3	1.1– 48.7
V	87.10	83.20	0.21	0.26	25– 252	17– 227
W	1.66	1.66	0.40	0.37	0.5– 9.4	0.5– 20
Y	20.00	17.00	0.27	0.24	6– 115	6– 80
Yb	2.88	2.82	0.32	0.26	1– 18	1– 12
Zn	70.80	64.60	0.26	0.27	15– 388	9– 258
Zr	138.00	132.00	0.30	0.27	100– 790	100– 840

* In instances where an element is analyzed by more than one method, '1' indicates neutron activation, and '2' indicates ICP.

Site Duplicates

A good measure of the significance and reliability of data can be obtained by determining correlations among site duplicates. Scatterplots of data from 12 pairs of site duplicates are presented in Figure 2. Data include Ag, Au, Mo, Sb, Ta, and W in <63 and 63 to 500 μm fractions of overbank sediment and in <63 and <180 μm fractions of active sediment.

Of the six elements plotted, Ag shows the most pronounced variation with size fraction. Of the four silver plots, only the <63 μm overbank fraction shows any correlation (0.64)-16 of 24 analyses have detectable Ag. Of the remaining 70 analyses, only two have detectable levels of Ag.

The effect of size fraction (and sample type) is also pronounced for Au. The scatterplot of Au in the <63 μm overbank samples is the only one of the four plots with good correlation (0.54). Five of the nine sample pairs analyzed that have detectable Au in both splits are in this fraction. The

Table 2. Means, standard deviations and data ranges of <63 μm and <180 μm fractions of active stream sediment. Means and ranges in g/t unless otherwise specified (N=49)

	GEOMETRIC MEAN		STANDARD DEVIATION (log)		DATA RANGE	
	<63 μm	<180 μm	<63 μm	<180 μm	<63 μm	<180 μm
Ag	0.06	0.05	0.17	0.09	0.05– 0.3	0.05– 0.2
As	26.90	19.50	0.57	0.58	1.9– 557	2.2– 575
Au (mg/t)	2.14	1.51	0.49	0.46	1– 80	1– 536
Ba	372.00	417.00	0.21	0.22	85– 1430	76– 1619
Ba1*	363.00	479.00	0.35	0.28	25– 1700	25– 2000
Br	11.80	5.75	0.40	0.34	0.2– 91.8	1– 34
Cd	0.23	0.18	0.26	0.27	0.1– 0.9	0.1– 0.9
Ce	87.10	55.00	0.27	0.16	17– 557	21– 148
Ce1	89.10	52.50	0.29	0.19	13– 553	14– 170
Co	12.00	9.77	0.36	0.39	2– 57	1– 63
Co1	15.90	12.30	0.39	0.39	2– 71	2– 82
Cr	186.00	166.00	0.42	0.41	10– 700	10– 1500
Cs	5.25	5.37	0.19	0.17	0.8– 15	2.1– 13
Cu	15.10	10.00	0.34	0.38	2– 70	1– 60
Dy	5.50	4.17	0.21	0.19	1.7– 18.1	2.1– 13.4
Eu	0.66	0.60	0.22	0.17	0.5– 2.5	0.5– 1.9
Fe (%)	2.09	1.74	0.18	0.21	0.65– 4.21	0.42– 4.63
Fe1 (%)	4.17	3.31	0.18	0.22	1– 10	0.65– 9.1
Ga	20.40	20.00	0.10	0.11	14– 35	9– 34
Hf	22.40	5.75	0.48	0.23	0.5– 281	1.8– 28
La	37.20	24.60	0.26	0.15	7– 283	9– 71
La1	37.20	22.90	0.27	0.15	7– 256	8– 62
Li	35.50	34.70	0.17	0.17	17.8– 87.7	17.3– 77.9
Lu	0.40	0.30	0.40	0.35	0.1– 3.3	0.1– 1.5
Mn	692.00	525.00	0.40	0.43	137–10210	123–11620
Mo	1.20	1.35	0.45	0.43	0.5– 15	0.5– 15
Na (%)	1.38	1.41	0.16	0.16	0.23– 2.25	0.34– 2.65
Nb	11.20	9.55	0.36	0.25	1– 90	2– 49
Ni	28.80	15.90	0.34	0.41	4– 135	1– 96
Ni1	22.40	15.50	0.51	0.42	5– 130	5– 85
Pb	16.60	13.80	0.29	0.25	3– 125	5– 123
Rb	91.20	97.70	0.21	0.20	26– 300	29– 310
Sb	1.23	1.02	0.36	0.38	0.18– 6.6	0.2– 5.8
Sc	12.30	10.50	0.17	0.21	5.3– 32.8	2.8– 30.1
Sm	8.13	5.25	0.24	0.14	1.6– 28.9	1.9– 13.9
Sr	115.00	110.00	0.25	0.25	23– 344	18– 316
Ta	2.14	1.38	0.34	0.24	0.2– 18	0.2– 7.6
Tb	1.32	0.89	0.32	0.21	0.2– 5.5	0.2– 2.9
Th2	3.39	3.16	0.70	0.57	0.5– 194	0.5– 65
Th1	13.20	8.32	0.34	0.24	3.9– 190	3.2– 58.8
U	5.37	2.95	0.32	0.20	1.7– 40.1	1– 10
V	89.10	79.40	0.24	0.26	16– 295	10– 256
W	2.57	2.51	0.46	0.49	0.5– 27	0.5– 124
Y	25.10	20.40	0.26	0.21	8– 121	9– 68
Yb	5.50	3.24	0.29	0.27	1– 28	1– 11
Zn	81.30	67.60	0.23	0.23	24– 258	28– 260
Zr	776.00	170.00	0.64	0.34	100–13000	100– 1300

* In instances where an element is analyzed by more than one method, '1' indicates neutron activation, and '2' indicates ICP.

The correlation of 0.30 in the <180 μm active sediment fraction may be misleading as it is strongly influenced by a single sample with detectable Au in both splits.

The effect on Mo is more equivocal than in the cases of Ag and Au. Scatterplots of both fractions of overbank sediment are very similar; both fractions have 7 of 12 sample pairs having detectable Mo in both splits. The plot of Mo in <63 μm active sediment indicates this fraction has the poorest correlation of the four and the fewest pairs (2) with detectable Mo in both splits. The <180 μm fraction of active sediment has the best correlation (0.69) although it has fewer pairs (5) with detectable Mo in both splits than do either of the overbank fractions.

The scatterplots of antimony (Sb) have the strongest correlations of the six elements plotted and appear unaffected by variation in size fraction. The correlations are excellent in all four plots, being slightly stronger in the active sediment fractions (0.99) than in the overbank fractions (0.96).

The scatterplots of Ta show two influences at work. The fine fractions of both sample types are enriched relative to the coarse fractions. The active sediment samples are enriched

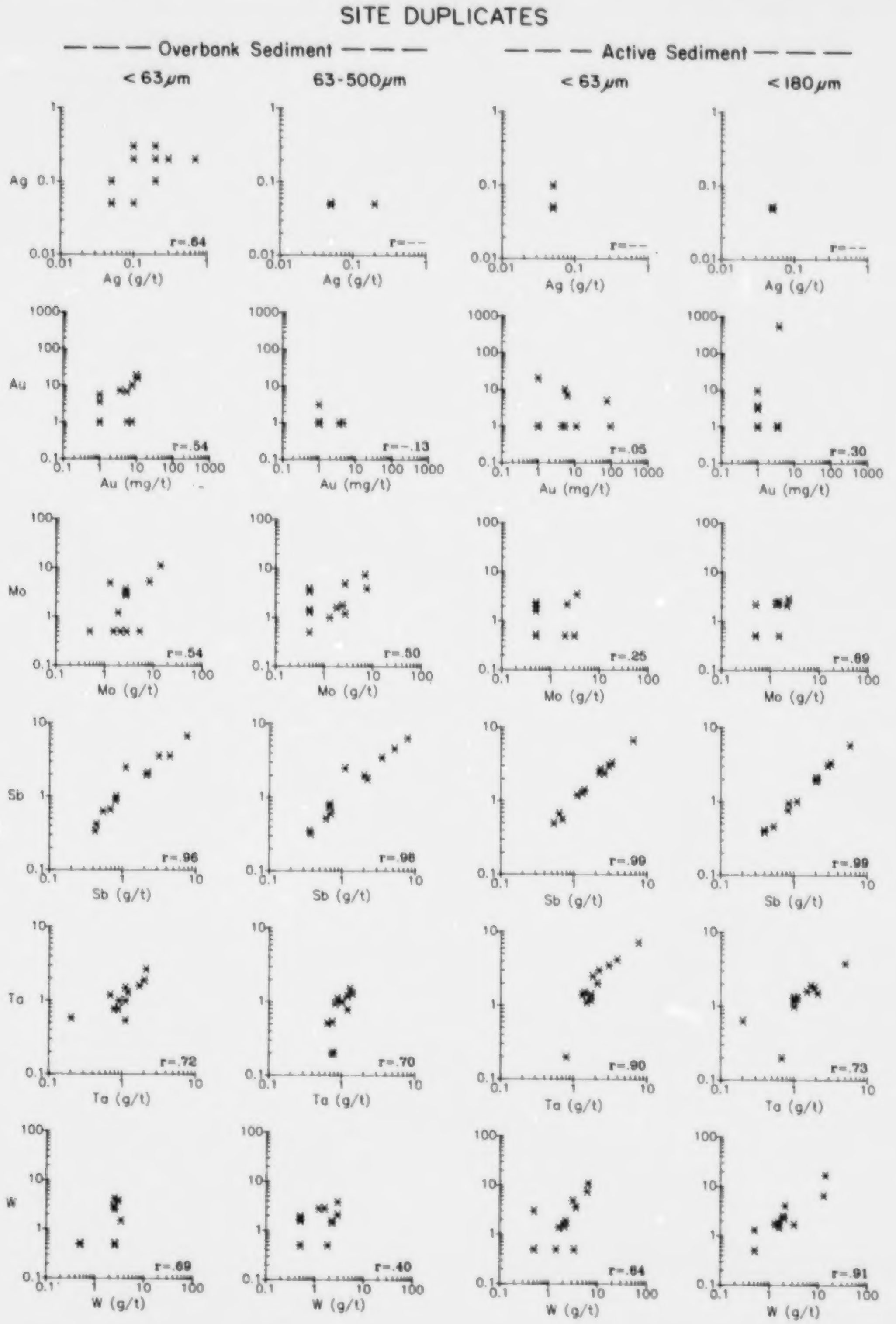


Figure 2. *Scatterplots of 12 pairs of site duplicates of Ag, Au, Mo, Sb, Ta, and W in < 63 μm and 63 to 500 μm fractions of overbank sediment and in < 63 μm and < 180 μm fractions of active sediment (r=correlation coefficient of $\log_{10}$ data).*

Table 3. Means, standard deviations and data ranges of 13 pairs of sample splits of overbank sediment prepared by normal preparation and by 30 percent H_2O_2 oxidation. Means and ranges in g/t unless otherwise specified

	GEOMETRIC MEAN		STANDARD DEVIATION (log)		DATA RANGE	
	Normal Prep.	H_2O_2 Prep.	Normal Prep.	H_2O_2 Prep.	Normal Prep.	H_2O_2 Prep.
Ag	0.08	0.06	0.32	0.13	0.05– 0.3	0.05– 0.1
As	29.50	49.00	0.49	0.50	2.6– 99.4	5.2– 177
Au (mg/t)	2.45	4.68	0.53	0.43	1– 24	1– 14
Ba	363.00	468.00	0.07	0.07	246– 441	321– 577
Ba1*	372.00	490.00	0.15	0.12	130– 500	210– 640
Br	21.90	1.66	0.28	0.41	10– 94.8	0.2– 7.3
Cd	0.19	0.22	0.25	0.22	0.1– 0.7	0.1– 0.7
Ce	77.60	87.10	0.13	0.26	53– 135	14– 156
Ce1	81.30	100.00	0.14	0.12	55– 130	71– 160
Co	13.20	10.50	0.13	0.12	8– 27	6– 18
Co1	14.50	12.00	0.13	0.16	10– 29	5.5– 21
Cr	105.00	129.00	0.23	0.17	30– 190	54– 200
Cs	6.31	8.13	0.15	0.18	4.3– 17	5.1– 26
Cu	23.40	22.40	0.17	0.11	12– 45	16– 34
Dy	3.89	4.68	0.11	0.11	2.9– 6.8	3.3– 8.3
Eu	0.85	0.93	0.23	0.24	0.5– 1.9	0.5– 2.1
Fe (%)	2.51	3.24	0.11	0.12	1.82– 3.71	2.1– 4.85
Fe1 (%)	3.39	4.68	0.10	0.12	2.4– 5.1	2.8– 7.3
Ga	19.50	26.30	0.06	0.08	15– 25	19– 35
Hf	9.12	9.55	0.16	0.12	4.8– 20	6.2– 16
La	33.90	41.70	0.14	0.12	22– 65	27– 72
La1	31.60	39.80	0.13	0.12	22– 60	28– 64
Li	32.40	41.70	0.13	0.13	19.9– 52.1	25.4– 71.2
Lu	0.21	0.27	0.28	0.31	0.1– 0.43	0.1– 0.59
Mn	617.00	372.00	0.54	0.36	89– 2520	79– 908
Mo	1.91	2.04	0.46	0.54	0.5– 10	0.5– 20
Na (%)	1.20	1.32	0.08	0.07	0.8– 1.6	0.92– 1.6
Nb	8.71	11.00	0.15	0.14	6– 17	6– 20
Ni	22.90	22.90	0.27	0.22	8– 58	8– 48
Ni1	10.70	19.50	0.38	0.42	5– 40	5– 59
Pb	17.40	31.60	0.21	0.16	9– 34	14– 64
Rb	81.30	112.00	0.16	0.17	55– 200	62– 310
Sb	1.78	2.45	0.44	0.44	0.44– 7.8	0.53– 11.5
Sc	9.77	12.30	0.04	0.05	8.8– 13	11– 15
Sm	7.08	8.91	0.11	0.11	4.7– 10.8	6.3– 13.1
Sr	97.70	102.00	0.17	0.17	51– 230	59– 233
Ta	1.17	1.62	0.16	0.18	0.68– 2.7	0.82– 3.9
Tb	1.05	1.32	0.09	0.10	0.81– 1.6	0.95– 2.2
Th2	5.62	5.25	0.42	0.48	0.5– 18	0.5– 13
Th1	10.70	14.10	0.17	0.15	5.5– 20.8	7.2– 24.9
U	4.57	5.13	0.25	0.25	1.9– 15	2.3– 19
V	75.90	104.70	0.08	0.08	56– 114	75– 139
W	2.09	7.00	0.37	0.29	0.5– 5.5	0.5– 5.2
Y	16.60	19.10	0.12	0.12	11– 28	13– 32
Yb	3.63	3.55	0.06	0.08	2.6– 4.6	2.3– 4.8
Zn	66.10	75.90	0.17	0.15	37– 134	42– 144
Zr	170.00	275.00	0.36	0.44	100– 600	100– 1000

* In instances where an element is analyzed by more than one method, '1' indicates neutron activation, and '2' indicates ICP.

relative to the overbank samples. In both types, correlations are better in the fine fractions.

Tungsten differs the most from the other elements plotted. Of the four plots, the <180 μm fraction of active sediment has the best correlation (0.91) and the most samples with detectable W in both splits.

SAMPLE PREPARATION BY PEROXIDE TREATMENT

Basic statistics are provided in Table 3 to permit comparison of the effects of two different sample preparation methods on the distribution characteristics of the data populations. Data from thirteen samples that were split and

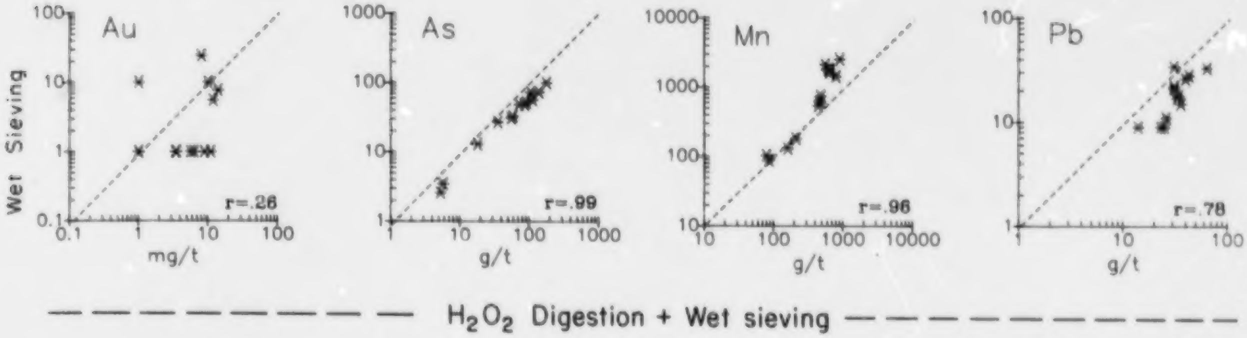


Figure 3. *Scatterplots of Au, As, Mn and Pb in 13 pairs of sample splits of < 63 μm overbank samples comparing wet-sieved preparation with preparation by 30 percent H_2O_2 oxidation followed by wet-sieving.*

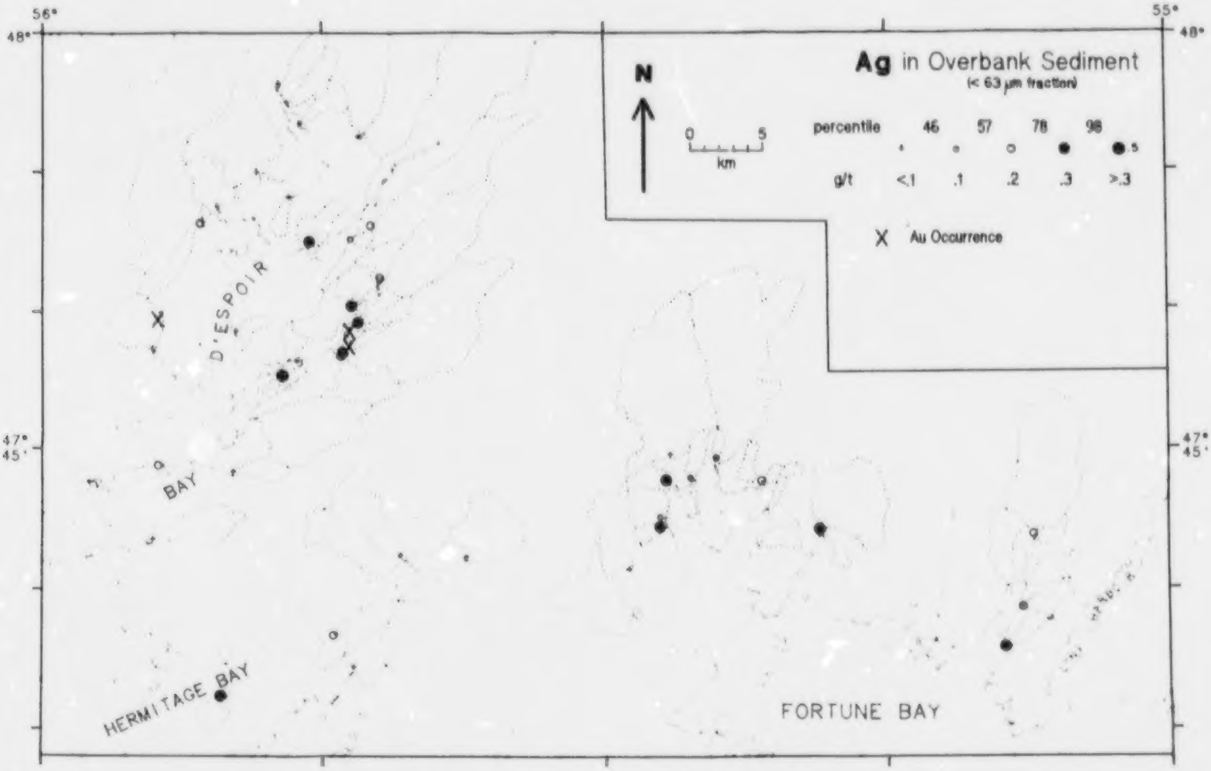


Figure 4. *Distribution of Ag in < 63 μm (< 250 mesh) fraction of overbank sediment in Bay d'Espoir area. Sampled catchment basins are enclosed by dotted lines.*

prepared as described previously are compiled. For most elements, mean values in the samples prepared by 30 percent H_2O_2 digestion are higher than in the normally prepared samples. Values in this group are 39 to 80 percent higher for the elements As, Au, total iron (FeI), Ga, Pb, Rb, Sb and Ta. For two elements, the reverse situation is true. Bromine is virtually eliminated and Mn values are much lower in the samples oxidized by H_2O_2. The scatterplots in Figure 3 graphically show the differences in the analytical results from the two preparation methods for Au, As, Mn and Pb.

DATA DISTRIBUTION MAPS

Symbol maps showing the distribution of values for two elements, Ag and Au, are included to illustrate the effects on distribution patterns of different size fractions and sample types.

Silver was selected because it shows highly contrasting analytical responses in different size fractions; gold also has higher concentrations in the fine fractions of both media (Figure 2 and Tables 2 and 3). Figures 4 to 6 display the

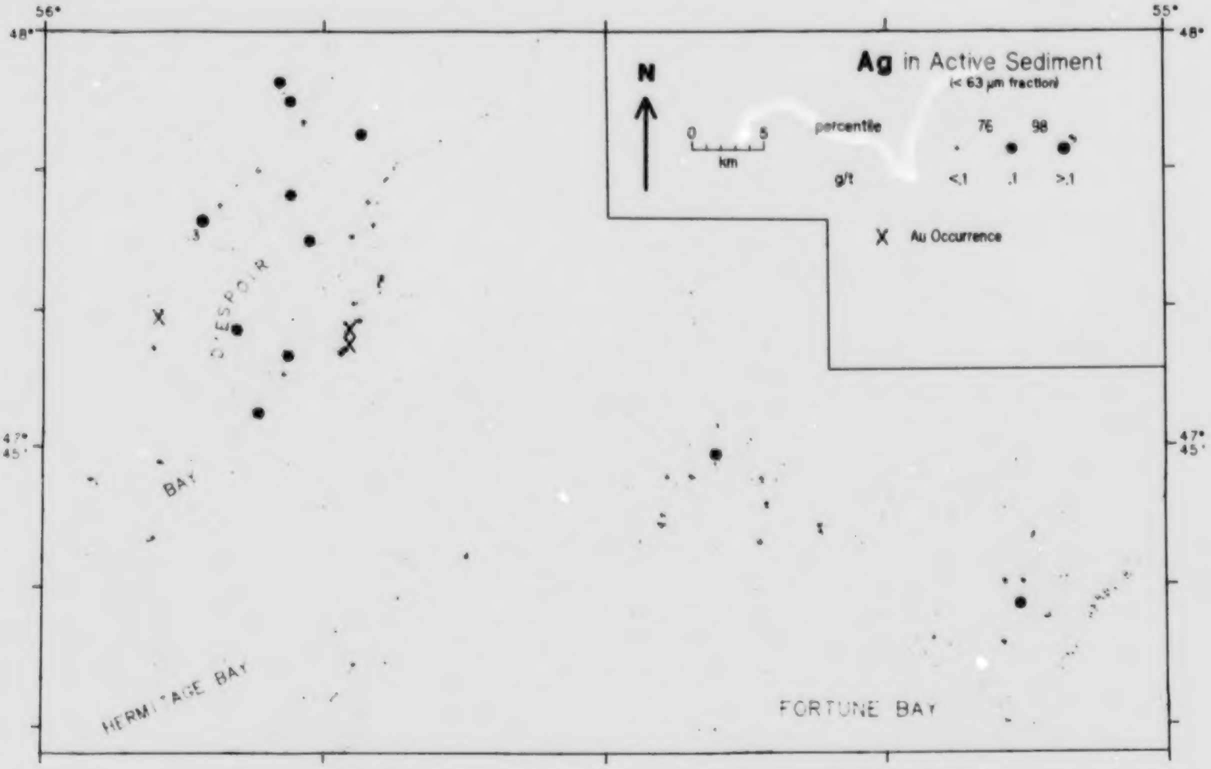


Figure 5. *Distribution of Ag in <63 µm (<250 mesh) fraction of active stream sediment in Bay d'Espoir area. Sampled catchment basins are enclosed by dotted lines.*

distribution of Ag in <63 µm overbank, <63 µm active sediment and <180 µm active sediment, respectively. The patterns are clearly varied. The map of Ag in <63 µm overbank sediment (Figure 4) contains the most samples with detectable Ag. Most of the highest values cluster around the two gold occurrences east of Bay d'Espoir. In contrast, most of the high Ag values in <63 µm active sediment are located to the west and north of Bay d'Espoir (Figure 5). The distribution of Ag in the <180 µm (<80 mesh) fraction of active sediment (Figure 6) is included to illustrate the almost complete lack of geochemical response in the fraction that is usually analyzed in stream-sediment surveys.

Figures 7 and 8 depict the distribution of Au in <63 µm overbank and <63 µm active sediment. For sites with duplicate samples, the mean (geometric) value of gold is plotted. The highest Au in the overbank samples (24 mg/t) is from the only catchment basin that actually contains known mineralization. The two gold occurrences to the east of Bay d'Espoir are very close to sampled basins and may be reflected by the sample of active sediment having 8.1 mg/t Au.

DISCUSSION

SIZE FRACTIONS

The effect of different size fractions on geochemical response varies widely by element. For most elements analyzed in this study, the fine fractions of both overbank and active sediment have higher concentrations than the corresponding coarse fractions (Tables 1 and 2). Other factors being equal, it is advantageous to have higher concentrations when interpreting data as these improve the signal-to-noise ratio by increasing the contrast with background and by improving the precision of analyses. This is particularly true of elements for which many samples have values at or near the detection limit. Elements for which detection limits are a problem and which yield higher values in the fine fraction of overbank sediment include Ag, Au, Cd, Hf, Mo and Ta. As noted above, the tendency toward element enrichment in the fine fraction is even more pronounced in active sediment than in overbank sediment.

Scatterplots of site duplicates (Figure 2) of fine and coarse fractions serve to reinforce the desirability of selecting the fine fraction for analysis of most elements, particularly for overbank sediment. Correlation among site duplicates is generally stronger in the fine fraction of overbank; silver is the most extreme example. Only Ag data from the fine fraction of overbank sediment has any correlation (r=0.64). Most samples of other fractions are at or below the 0.1 g/t detection limit. Similarly for gold, of all the fractions, only the fine fraction of overbank shows a significant correlation among its duplicates. However, for some elements, particularly Cr, Mo and W, the <180 µm fraction of active

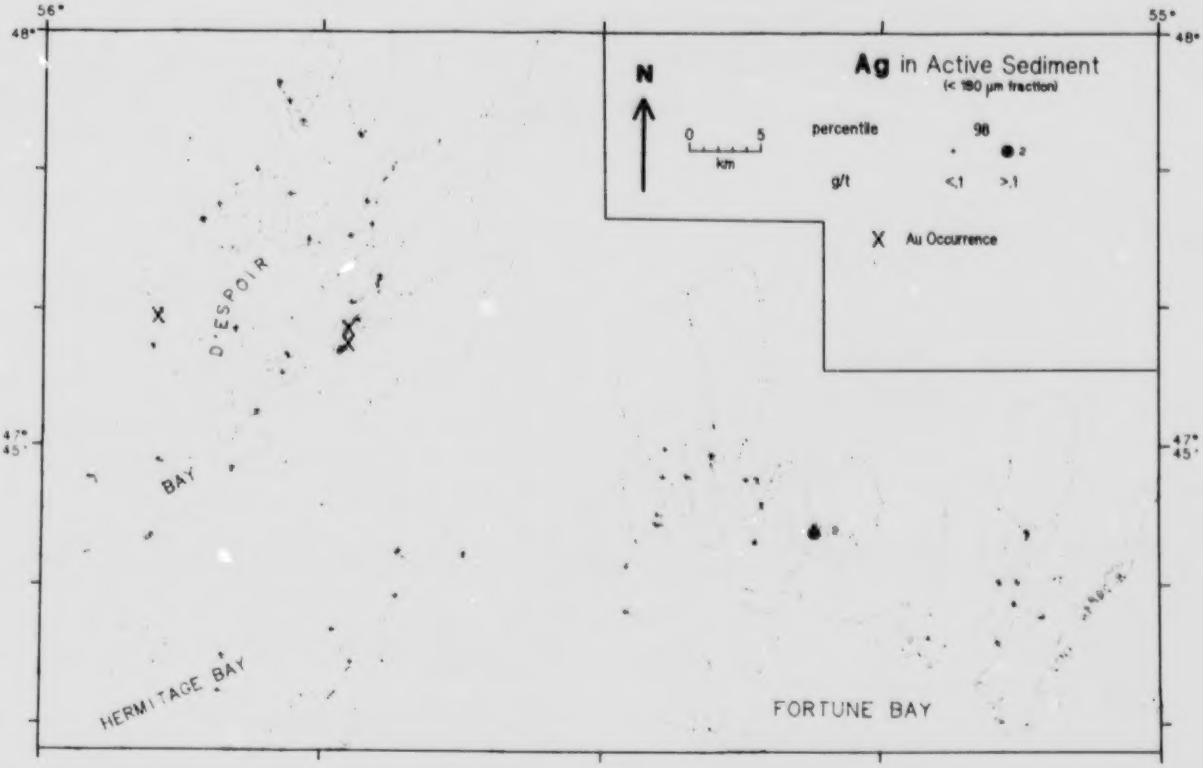


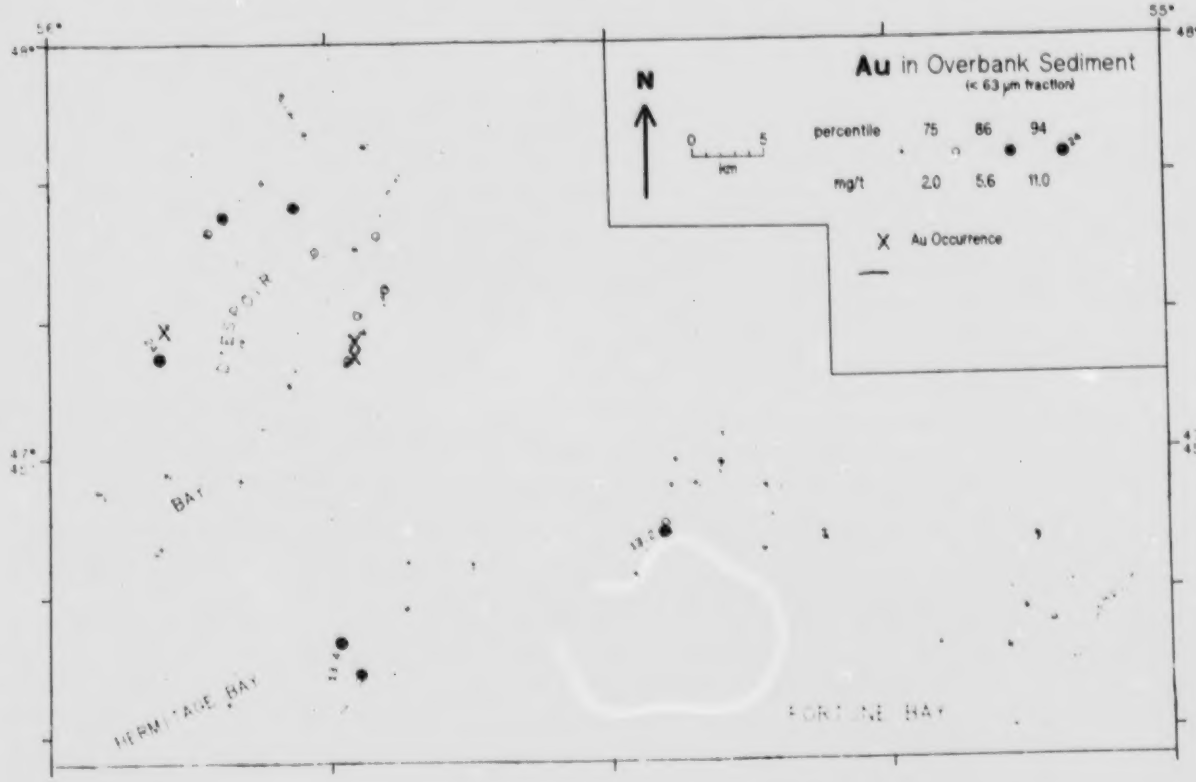
Figure 6. *Distribution of Ag in <180 µm (<80 mesh) fraction of active stream sediment in Bay d'Espoir area. Sampled catchment basins are enclosed by dotted lines.*

sediment has significantly stronger correlations than does the <63 µm fraction suggesting that these elements occur in minerals that are more homogeneously distributed in the coarse fraction.

An important point to remember when comparing correlations of site duplicates of active sediment with site duplicates of overbank sediment, is the dissimilar nature of the two sample types. Samples of active sediment represent a 'snapshot' of sediment composition at a given time. The sediment composition at a given site following changes in water levels, Eh conditions, sediment sources or transport conditions may be quite different. Moreover, the method of collecting active sediment, whereby it is a composite of several sites within a small area, would tend to increase the homogeneity and similarity of site duplicates. However, for overbank samples there is little or no expectation of composition change with changing stream conditions as the sample already is a composite of multiple flooding episodes over a long period of time. A single flooding event would not substantially change the composition of the overbank profile. Thus, although the correlations of active sediment duplicates may appear better, when the time factor is considered it makes the comparisons uncertain.

SAMPLE PREPARATION

Basic statistics are presented in Table 3, tabulating the analytical results of two sample-preparation procedures applied to 13 pairs of sample splits of overbank sediment. Of the two methods, the 30 percent H_2O_2 oxidation procedure resulted in considerably higher concentration levels in the fine fraction for many trace elements including gold. Not illustrated, but present, was a corresponding drop in the relative concentration levels in the coarse fraction. This enrichment trend likely results from the fact that many mineral phases that are enriched in trace elements in sediments are finer grained than the more resistate and abrasion-resistant quartz and feldspar grains. If this fine material is cemented into composite grains, they would remain in the coarse fraction with the quartz and feldspar during normal sieving. By disaggregating these composite grains with a process such as H_2O_2 oxidation prior to analysis, the resulting data should have improved the analytical precision and signal-to-noise ratios. This step will reinforce the effect already initiated by analyzing the fine fraction rather than the coarse.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Au in Overbank Sediment
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HERMITAGE BAY
FORTUNE BAY
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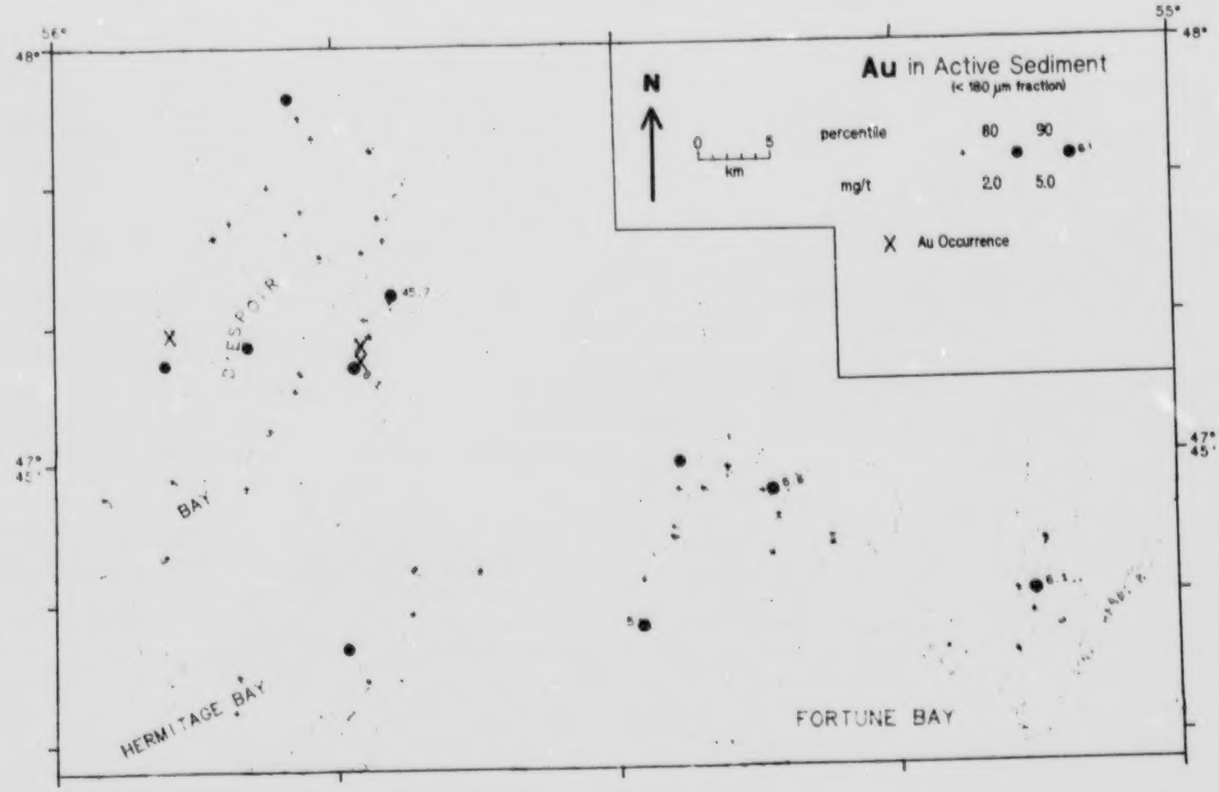
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X Au Occurrence
D'ESPOIR
BAY
HERMITAGE BAY
FORTUNE BAY
45.7
6.6

CONCLUSIONS

These observations are made on a modest-sized dataset from only one area and should be regarded as tentative, until confirmed by similar results from elsewhere. Nonetheless, certain conclusions and recommendations are warranted.

There appears to be no single, best sieve size to use for preparing overbank or active stream sediment for analysis, as results vary according to the element. However, analytical precision and concentration levels may be increased for most elements by analyzing the <63 μm fraction of overbank sediment rather than a coarser fraction. In overbank sediment, this effect is most pronounced for Ag, Au, Br, Cd, Ce, Cu, Hf, Pb, Sm, Ta and U. The same conclusion applies, in general, to active stream sediment, where contrast between fine and coarse fractions is even stronger. The elements most enhanced in the fine fraction of active sediment are As, Au, Br, Ce, Cu, Hf, La, Ni, Sm, Ta, Tb, U and Yb. However, for Ba in both sample types, for Cr in overbank sediment, and for Mo and W in active sediment, the information provided by the coarser fraction appears superior.

A sample preparation procedure that separates composite mineral grains, such as oxidation by 30 percent H_2O_2 prior to sieving, can enhance data precision for many elements by increasing the concentration levels in the fine fraction. One side effect of the method, however, is the virtual elimination of Br and organic matter.

ACKNOWLEDGMENTS

We would like to thank Sean O'Brien for helpful discussions of the geology in the study area, Hank Williams and Alex Pittman for sharing their house and many fine stories with us in St. Albans, and Peter Davenport for general discussions of geochemistry and constructive criticism of the manuscript.

REFERENCES

Brewer, K. and O'Driscoll, C.F.
1986: Mineral Occurrence Map of St. Alban's map sheet. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 8680.

Davenport, P.H., Nolan, L.W., O'Brien, S.J. and Honarvar, P.
1990: Gold and associated elements in lake sediment from regional surveys in the Belleoram map area. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File 1M (312).

McConnell, J.W. and Honarvar, P.
1991: A comparison of overbank and stream sediment as geochemical sample media in southern Newfoundland (1M). Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File 1M (319).

O'Brien, S.J., O'Driscoll, C.F. and Colman-Sadd, S.P.
1981: Geological compilation of the Belleoram and St. Lawrence map areas (1L and 1M). Newfoundland Department of Mines and Energy, Mineral Development Division, Map 81116.

Ottesen, R.T., Bogen, J., Bolviken, B. and Bolden, T.
1989: Overbank sediment: a representative sample medium for regional geochemical mapping. Journal of Geochemical Exploration, Volume 32, pages 257-277.

Figure 7 *(top of page 298). Distribution of Au in <63 μm (<250 mesh) fraction of overbank sediment in Bay d'Espoir area. Sampled catchment basins are enclosed by dotted lines.*

Figure 8 *(bottom of page 298). Distribution of Au in <180 μm (<80 mesh) fraction of active stream sediment in Bay d'Espoir area. Sampled catchment basins are enclosed by dotted lines.*

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GOLD METALLOGENY, EASTERN DUNNAGE ZONE CENTRAL NEWFOUNDLAND

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Mineral Deposits Section

ABSTRACT

Rocks of the northeastern Dunnage Zone, particularly those belonging to the Botwood and Davidsville groups, are proving to be a significant exploration target for structurally controlled gold mineralization.

Preliminary results indicate that two broad classes or styles of gold mineralization are developed in the area: mesothermal, shear-zone related auriferous quartz veins, locally accompanied by intense Fe-carbonate alteration; and epithermal style, low-grade gold mineralization associated with spectacular hydrothermal brecciation, silicification and locally intense argillic alteration.

The gold occurrences appear to be spatially related to a complex network of northeast-, north-northeast- and northwest-trending linears. These linears may have acted as loci for the mineralizing fluids.

INTRODUCTION

A metallogenic study of gold mineralization hosted by rocks of the eastern Dunnage Zone (i.e., south and east of the Red Indian Line) was initiated in the fall of 1989. The main thrust of this study is to document the styles and settings of the numerous gold occurrences recently found in the area. During 1990, fieldwork concentrated on gold mineralization located in the northeastern portion of the zone, particularly within the Middle Ordovician Davidsville Group and the Silurian Botwood Group. This work involved detailed grid and trench mapping, diamond-drill core logging and regional rock sampling for assaying.

Access to the area is provided by the Trans-Canada and the Gander Bay highways, and by an extensive network of forest access roads, which lead north and south from Glenwood and south from the Gander Bay and Horwood areas. The region is characterized by gently undulating topography that comprises heavily forested tracts, large cutover areas, long, narrow lakes and extensive bogs. The north to northeast trend of the numerous lakes and streams reflects the strong bedrock lithological and structural control on their orientation. Extensive glacial till covers the entire region resulting in limited bedrock exposure.

REGIONAL SETTING

The study area lies within the Dunnage Zone of Williams (1979) near its boundary with the Gander Zone (Figure 1). The Dunnage Zone records pre-accretionary and accretionary events related to the development and destruction of the early Paleozoic Iapetus ocean. The geological evolution of the region can be subdivided into two broad stages involving pre- and post-accretionary events (Swinden, 1990). The Dunnage Zone records both pre-accretion volcanism and pre- and syn-accretion sedimentation in a series of Cambrian to Middle Ordovician island arcs and back-arc basins. Cessation of volcanism coincided with the emplacement of the Taconic allochthons during the Middle Ordovician. During the late Ordovician and Early Silurian, the continued closure of the Iapetus Ocean resulted in the deposition of flyschoid sequences in fault-bound basins in the central and eastern Dunnage Zone.

The Davidsville Group is interpreted to have formed as a distal back-arc turbidite sequence derived from the volcanic arcs to the west, and deposited on an ophiolitic basement (Blackwood, 1982). Dismembered sections of the ophiolitic basement are represented by rocks of the Gander River Ultrabasic Belt (Jenness, 1958; Blackwood, 1982), referred to as the Gander River complex by O'Neill and Blackwood (1989).

In north-central Newfoundland, shelf facies rocks of the Gander Zone are interpreted to locally pass conformably westward into rocks of the Davidsville Group (Blackwood, 1982). Regionally, the Dunnage Zone is interpreted to be allochthonous upon rocks of the Gander Zone (Colman-Sadd and Swinden, 1984).

Post-accretion events, marked by the activation or reactivation of large strike-slip faults, the development of pull-apart basins (Szybinski *et al.*, 1990) and crustal melting resulting in epicontinental-style volcanism (Coyle and Strong, 1987), led to the deposition of Silurian fluviatile sedimentary and terrestrial volcanic rocks. In east-central Newfoundland this post-accretionary stage is represented by the Botwood and Indian Islands groups. The Botwood Group comprises grey and red, locally micaceous, sandstone, minor fossiliferous calcareous beds and conglomerate. Blackwood (1982) interpreted the Botwood Group to be conformable on the Davidsville Group, representing a transition from submarine fan to deltaic environments. The Indian Islands Group comprises phyllitic slates, quartzitic and calcareous sandstones, thin limestone lenses, conglomerate (Baird, 1958) and minor felsic volcanic rocks (Patrick, 1957).

Acadian deformation, metamorphism, plutonism and reactivation of the major fault systems during the early Devonian resulted in intense deformation and plutonism within the eastern Dunnage Zone. Rocks of both the Davidsville and Botwood groups exhibit a regional, northeast-trending, penetratative cleavage that is axial planar to isoclinal folds. Within the Davidsville Group, this cleavage is quite slaty. Second-phase deformation structures within the Davidsville Group comprise small conjugate kink bands and minor, open to moderately tight, gently southward-plunging folds that fold the F_1 cleavage (Blackwood, 1982). The rocks have been subjected to greenschist-facies metamorphism.

Abundant small, fine- to medium-grained gabbroic bodies intrude the Davidsville and Botwood groups, particularly near their contact. These intrusions are generally undeformed except were they have been affected by shearing along north- and north-east trending shear zones. The gabbros are interpreted to be of Devonian age (Blackwood, 1982) and probably related to the Mount Peyton batholith to the south.

PREVIOUS WORK

The first recorded geological investigation in the area was undertaken by Alexander Murray and J.P. Howley (Murray and Howley, 1881). These workers examined the geology along eastern Notre Dame Bay, the Gander River and Gander Lake. Murray and Howley (1881) also reported the first known occurrence of gold mineralization within the area. They stated that, 'Distinct traces of this precious metal were ascertained in a quartz vein cutting the silky, bluish slates on the S.W. Gander River in 1876.' They also reported that innumerable quartz veins, which looked promising for gold mineralization, were exposed along the railway line north of Gander Lake.

A number of significant regional studies have been undertaken within the study area. Chromite mineralization, associated with the ultrabasic rocks to the east of the Gander River, were examined by Snelgrove (1934) as part a study of the chromite deposits of Newfoundland. Twenhofel and Shrock (1937) examined the Silurian rocks exposed along Hamilton Sound, particularly within the Dog Bay (Horwood Bay) area. Patrick (1956) interpreted that these rocks extended southwestward into the Second Pond area. Baird (1958) referred to these and similar rocks exposed on islands in Hamilton Sound as the Indian Islands Group. Twenhofel (1947) proposed that the sequence of phyllites, slates, argillites and quartzites exposed on the shores of Gander Lake be designated the Gander Lake Series.

In 1951, the Photographic Survey Corporation Limited conducted geological reconnaissance mapping of east-central Newfoundland for the Newfoundland Government (Baird *et al.*, 1951). This work covered a belt extending south from Hamilton Sound to Baie d'Espoir. Baird *et al.* (1951) reported an occurrence of native gold reported by the Independent Mining Corporation. The gold, associated with sphalerite, molybdenite, fine-grained pyrite and vuggy quartz hosted by greywacke, was reported to be located three quarters of a mile south of Middle Ridge Pond.

Jenness (1954, 1958) defined the Gander River Ultrabasic Belt and the Gander Lake Group. The Gander Lake Group, which was proposed to replace the Gander Lake Series of Twenhofel (1947), was sub-divided into lower, middle and upper units (Jenness, 1963).

Regional 1:250,000-scale mapping of the area was undertaken by the Geological Survey of Canada (Williams, 1964; Anderson and Williams, 1970).

Kennedy and McGonigal (1972) redefined the Gander Lake Group to include only the pelitic, semipelitic and psammitic rocks (the lower unit of Jenness, 1963) located to the east of the Gander River Ultrabasic Belt. They defined the fossiliferous Middle Ordovician slates, siltstones and greywackes (the middle and upper units of Jenness, 1963), which are developed to the west of the Gander River Ultrabasic Belt, as belonging to the Davidsville Group. The contact between the Davidsville Group and the Gander River Ultrabasic Belt was described by Kennedy (1975) as an unconformity.

The Gander River Ultrabasic Belt and the Davidsville Group in the Carmanville area were mapped by Currie *et al.* (1980) at a scale of 1:50,000 for the Geological Survey of Canada.

Systematic 1:50,000-scale mapping of the Gander River area (2D/10, Blackwood, 1981, 1983; 2D/11, Blackwood, 1981; 2D/15 and 2E/2, Blackwood, 1982; 2E/1, O'Neill, 1987, O'Neill and Knight, 1988; and 2D/15, O'Neill, 1990) was carried out by the Newfoundland Department of Mines and Energy. Blackwood (1982) interpreted that rocks of the Gander River Ultrabasic Belt, to the north of Gander Lake, are in fault contact with rocks of the Gander Group. To the south of Gander Lake, where the Gander River Ultrabasic Belt is not continuously exposed, Blackwood (1982) interpreted the contact between the Davidsville and Gander groups to be conformable. The contact between the Davidsville and Botwood groups was described as probably conformable. Blackwood (1979, 1982) reported that arsenopyrite- and pyrite-bearing quartz veins, developed within intensely sheared gabbro northeast of Jonathans First Pond, assayed 6 g/t gold.

O'Neill (1987) reported that the basal part of the Davidsville Group, in the Weir's Pond area, is structurally interleaved with the Gander River Ultrabasic Belt. O'Neill (1987) also reported the presence of minor gold mineralization, within a small granite that intrudes the Davidsville Group, and mineralized quartz veins developed in psammitic and semipelitic rocks of the Gander Group. He also suggested that the talc−carbonate alteration associated with the rocks of the Gander River Ultrabasic Belt is similar to that associated with the listwaenite model of Buisson and LeBlanc (1985).

O'Neill and Blackwood (1989) proposed a revised stratigraphic nomenclature for the Gander and Davidsville groups and the Gander River Ultrabasic Belt. They proposed to subdivide the Gander Group into the Jonathans Pond and Indian Bay Big Pond formations and the Davidsville Group into the Weir's Pond, Hunt's Cove and The Outflow formations. The Gander River complex was proposed to replace the Gander River Ultrabasic Belt.

The area was included in a regional lake-sediment geochemical survey by the Newfoundland Department of Mines and Energy (2E, Davenport and Nolan, 1988; 2D, Davenport *et al.*, 1988). This survey showed the distribution of a wide range of elements including Au, Sb and As. This data has proved valuable to companies in defining exploration targets, particularly in previously unexplored areas.

Exploration within the northeastern Dunnage Zone has occurred in three phases. Prior to 1970, the emphasis was largely restricted to exploration for chromite and asbestos associated with ultramafic rocks of the Gander River complex. The Newfoundland and Labrador Corporation Limited (NALCO) held concession rights to much of the area from 1951 to 1980. The company conducted extensive prospecting of the Gander River complex (Dunlop, 1955).

Between 1970 and the early 1980's, the emphasis shifted to base-metal exploration as a number of companies concentrated on the volcanic rocks associated with the Gander River complex. International Mogul Mines Limited optioned a portion of the NALCO ground during the 1970's and discovered a number of small base-metal showings, which were subsequently drilled.

In the early 1980's, following the discovery of quartz vein-hosted gold mineralization near Jonathans Pond (Blackwood, 1979, 1982), the emphasis in exploration shifted once again, this time to gold. Since then a number of companies have been active in the area: Westfield Minerals, Duval International Limited, Esso Minerals Limited, Gander River Minerals, Esso Resources Canada, Falconbridge and Noranda Exploration Company Limited. Noranda has been active, particularly in the Botwood and Davidsville groups, having made a number of significant gold discoveries through a combination of regional prospecting and geochemical soil- and lake-sediment sampling.

GOLD MINERALIZATION

Known gold occurrences within north-central Newfoundland have gone from a single showing in the early 1980's to at least 15 significant showings or prospects, the majority of which were discovered since 1988 (Figure 1). The mineralization is epigenetic, structurally controlled and occurs in a wide variety of rocks of varying ages. Gold is not confined to particular stratigraphic belts and is found in rocks of the Gander Group, the Gander River complex, and the Davidsville and Botwood groups. However, mineralization appears to be concentrated in the Davidsville and Botwood groups, particularly near their contact.

Initial results from the 1990 field season suggest two broad classes of gold occurrences, with characteristics of mesothermal and epithermal styles of mineralization, respectively. At least four styles or variations of the former type have been documented within the study area:

1) gabbro-hosted gold-bearing quartz−carbonate veins accompanied by intense Fe-carbonate alteration (Clutha, Big Pond and Jonathons Pond);

2) sediment-hosted gold-bearing quartz−carbonate veins accompanied by silicification and carbonate alteration (Stinger);

3) shear-zone hosted gold-bearing quartz−carbonate veins accompanied by minor carbonate alteration developed in shales and greywackes (Bullet); and

4) dilational quartz veins developed within deformed graphitic greywacke and shale (Bowater).

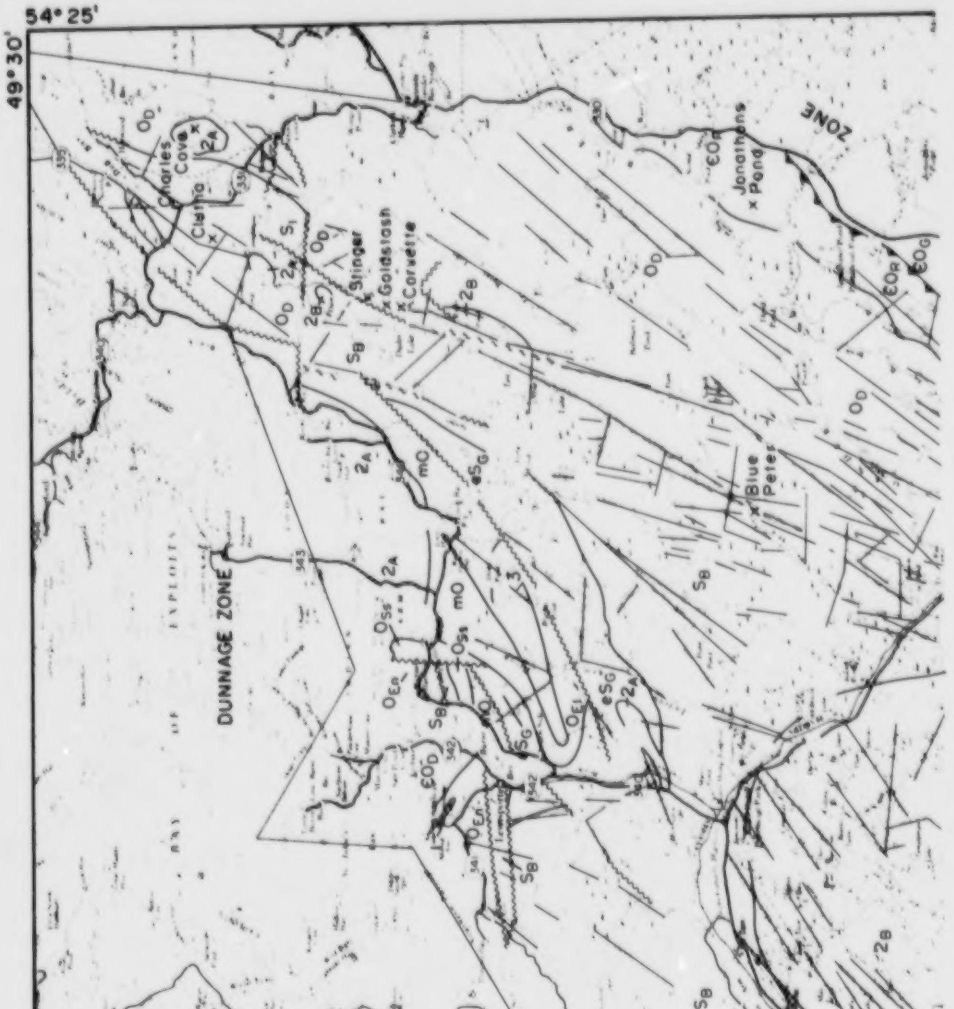
Epithermal-style mineralization typically contain low-grade gold accompanied by spectacular hydrothermal breccias, chalcedonic quartz and intense argillic alteration (Aztec and The Outflow).

MESOTHERMAL MINERALIZATION

Type 1

This style of gold mineralization is characterized by intense Fe-carbonate alteration haloes, which extend up to 2 m from the quartz veins; the quartz veins are discontinuous. They are, typically 2 to 10 cm thick (locally up to 50 cm), exhibit pinch- and swell-structures, and their orientation and distribution are controlled by the rheological properties of the gabbro bodies. The veins typically contain patches and disseminations of pyrite and crystals of arsenopyrite and, locally, spectacular free gold. Two variations of veining have been observed: shear-zone hosted veins and dilational veins.

The gabbro bodies are typically small, fine to medium grained, dark coloured, sill-like intrusions. They range from highly deformed to relatively undeformed, depending on the nature of the deformation in the surrounding rocks. The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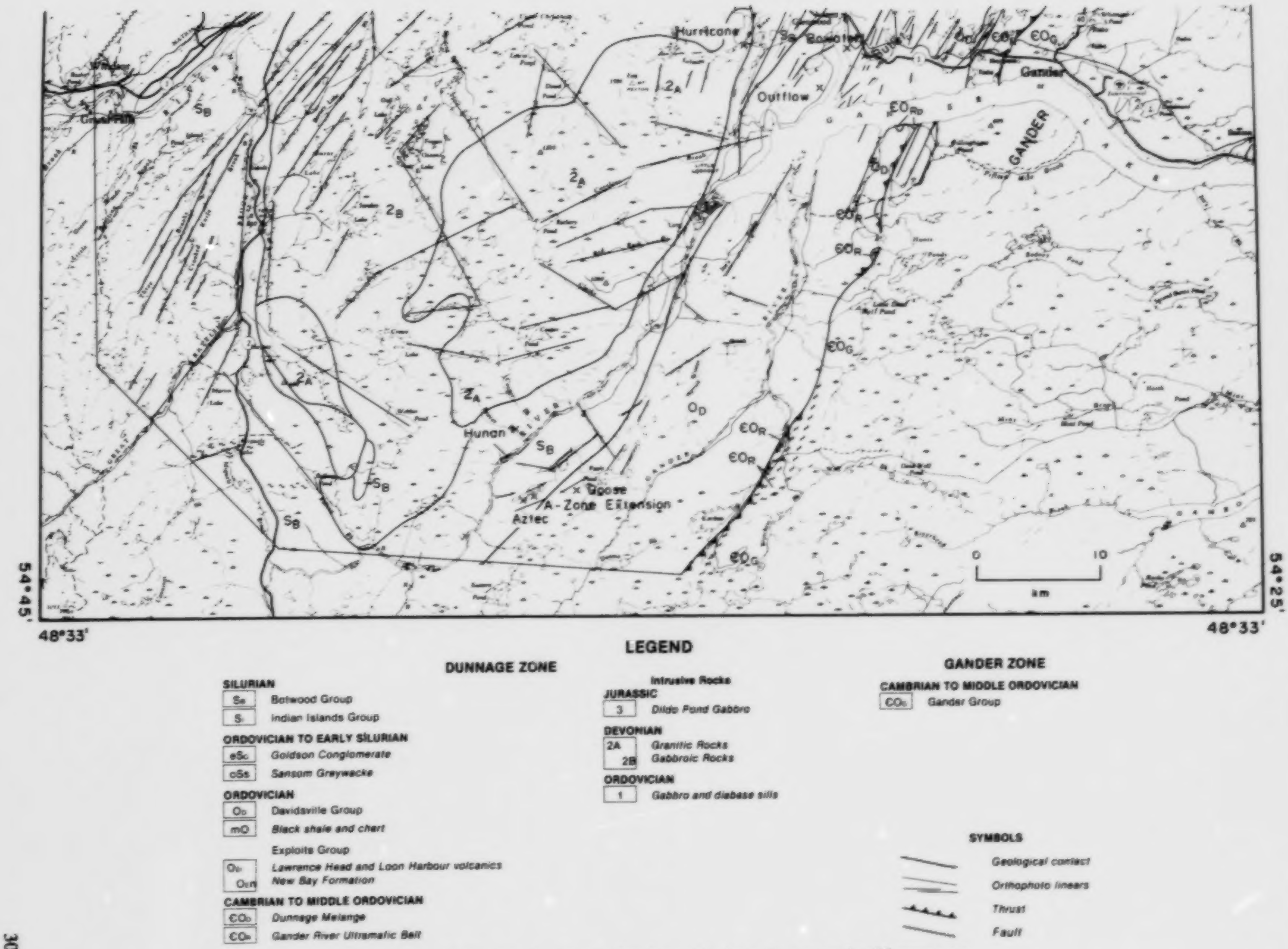

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LEGEND
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SILURIAN
S_B Botwood Group
S_I Indian Islands Group
ORDOVICIAN TO EARLY SILURIAN
eS_G Goldson Conglomerate
oS_S Sansom Greywacke
ORDOVICIAN
O_D Davidsville Group
mO Black shale and chert
Exploits Group
O_L Lawrence Head and Loon Harbour volcanics
O_{EN} New Bay Formation
CAMBRIAN TO MIDDLE ORDOVICIAN
$€O_D$ Dunnage Melange
$€O_R$ Gander River Ultramafic Belt
Intrusive Rocks
JURASSIC
3 Dildo Pond Gabbro
DEVONIAN
2A Granitic Rocks
2B Gabbroic Rocks
ORDOVICIAN
1 Gabbro and diabase sills
GANDER ZONE
CAMBRIAN TO MIDDLE ORDOVICIAN
$€O_G$ Gander Group
SYMBOLS
Geological contact
Orthophoto linears
Thrust
Fault

Figure 1. *Regional geology map showing orthophoto linears and gold prospects.*

gabbros are widespread throughout the Davidsville and Botwood groups. However, they appear to be concentrated along a linear belt that approximates the Botwood–Davidsville contact. This suggests a significant, regionally extensive, deep-seated structure, which governed the emplacement of these gabbro bodies, and may have provided a pathway for the later mineralizing fluids. Similar quartz veins, but with less intense Fe-carbonate alteration, are developed within deformed gabbros of the Gander River complex.

Clutha

Gold mineralization was discovered at Clutha (Figure 1) in 1988. At that time, the prospect was trenched and tested by fifteen diamond-drill holes. A channel sample from the prospect assayed 0.146 ounces/ton over 13.1 feet (Noront Resources Limited, 1990). The gold is hosted by pyrite- and arsenopyrite-bearing quartz–carbonate veins. These veins cut intensely Fe-carbonate altered and silicified, fine- to medium-grained gabbros, which are intruded into a monotonous sequence of black shale, siltstone and greywacke (Figure 2). The shales exhibit an intensely developed north-northeast trending, steeply east-dipping, slaty cleavage. Graded bedding in the greywacke units indicates that the rocks are overturned to the northwest.

These sedimentary rocks were mapped by Patrick (1956) and included in the Silurian Indian Islands Group by Baird (1958). However, the presence of intercalated, fine-grained, grey-green pillow lava along strike to the northeast as well as lithological similarity to the Davidsville Group, suggest that the belt of sedimentary rocks, which extend northward from Second Pond along the west side of Dog Bay, be included in the Davidsville Group.

The gabbro bodies range from approximately 2 to 20 m thick, have a strike length of up to 400 m and appear to be preferentially intruded along the belt described above as belonging to the Davidsville Group. However, the mineralization is confined to portions of the gabbros that underwent intense deformation. The gabbros appear to have been intruded during early regional deformation. Crosscutting relationships between the gabbros and the sedimentary rocks are preserved locally.

The quartz veins are typically 2 to 10 cm, but locally up to 50 cm thick, and discontinuous. Fine-grained, disseminated pyrite and arsenopyrite occur both in the veins and in the alteration haloes to the veins. Visible gold was observed in one quartz vein obtained from drill core. The Fe-carbonate-rich haloes extend up to 2 m from the veins. Abundant gold can be panned where the alteration and veining have been significantly weathered.

Two northeast-trending linear valleys are developed to the east and west of the prospect. Inferred sinistral movement on these structures would have resulted in clockwise rotation of the structural elements bounded by the two faults. This would result in the rotation of the gabbros into the plane of the regional foliation. This rotation produced conjugate

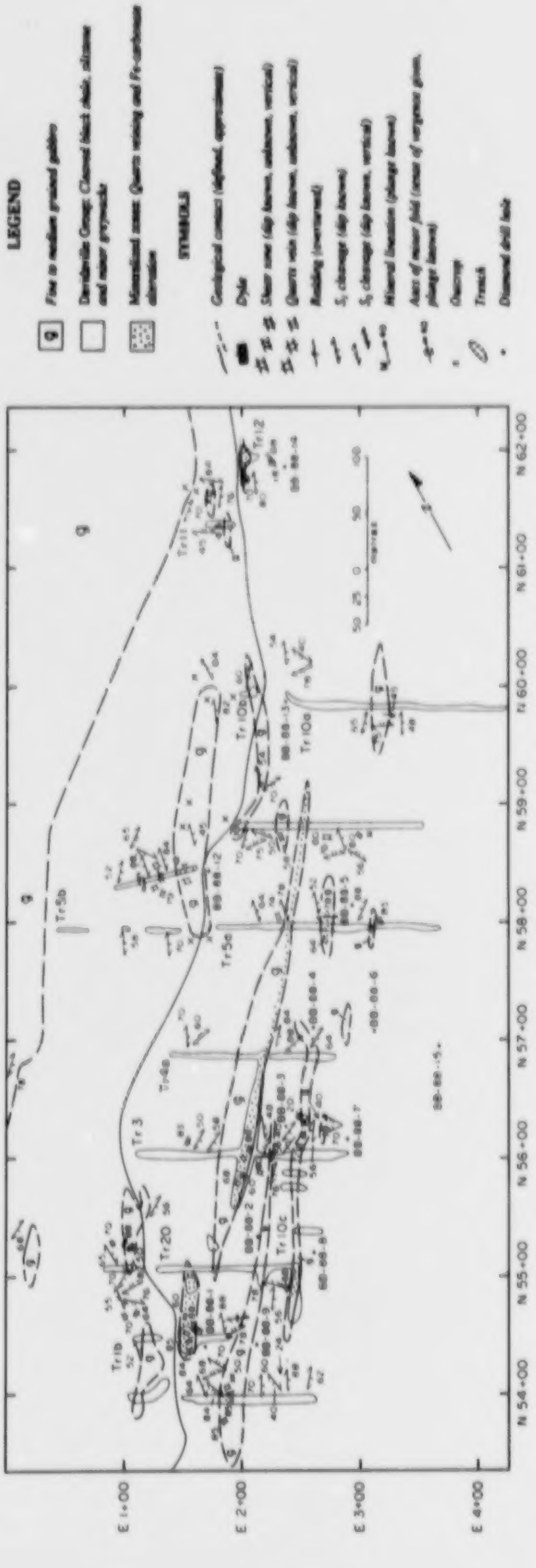


Figure 2. *Geology and trench map of the Clutha area.*

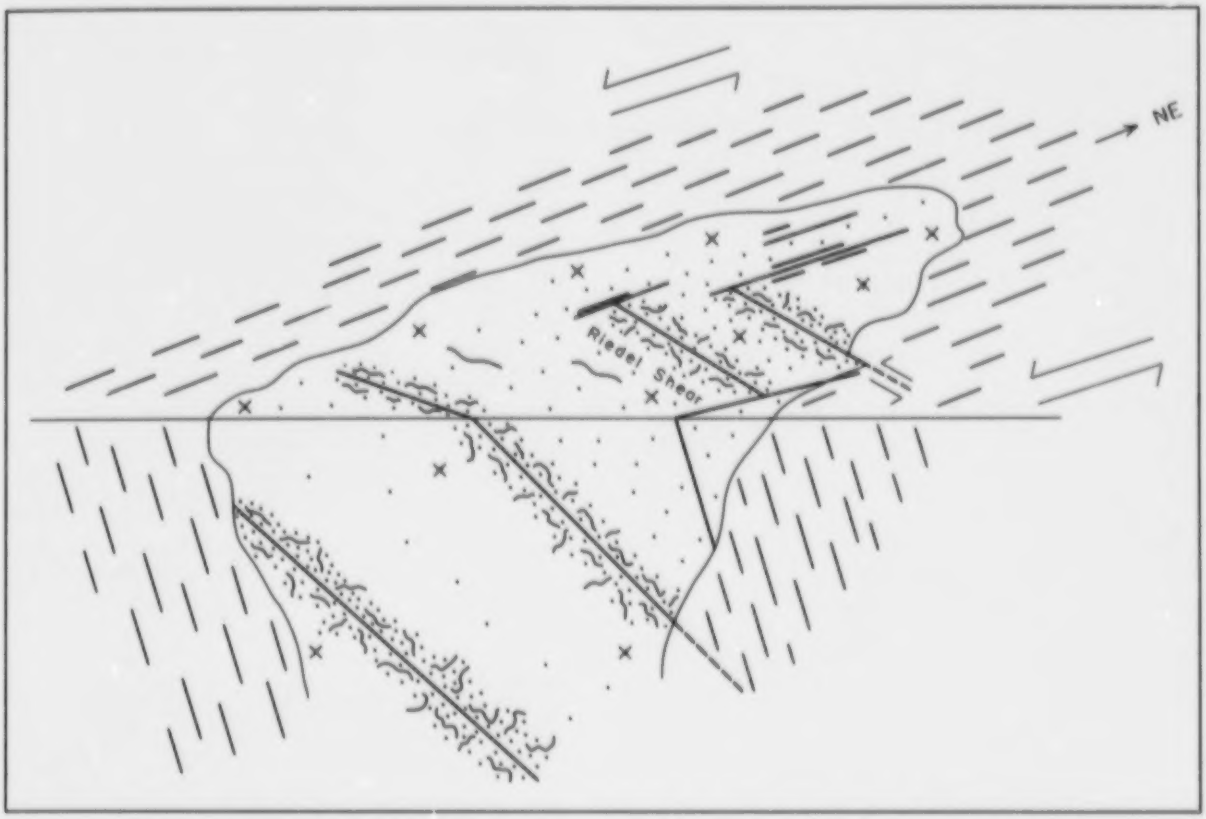


Figure 3. *Schematic diagram exhibiting the structures controlling gold mineralization at Clutha.*

jointing patterns as observed in the less deformed and altered gabbro bodies, and Riedel shears, conjugate Riedel shears and shears developed parallel to the regional foliation (Figure 3) in the deformed gabbros. Development of these structures can be related to rotational deformation (simple shear) of the strain ellipse (Figure 4).

These shears played a significant role in the localization of quartz veining and alteration with the most intense alteration appearing to have been developed along the conjugate Riedel shears (Plate 1). The veining and alteration mimicked the conjugate joints producing a blocky alteration pattern with remnent blocks of relatively unaltered gabbro being preserved (Plate 2). Mineralized zones within the gabbros are typically narrow, ranging from 2 to 10 m, and have a strike length that approximates that of the gabbro.

The conjugate Riedel shears intersect the gabbros at a relatively high angle, thereby limiting the strike potential of these shears to the width of the gabbro. When these shears intersect the surrounding shales they quickly die out, reflecting the competency difference between the gabbro and the shale. However, these shears are repeated regularly along the strike length of the gabbro, forming panels of shearing and alteration that dip variably to the northeast. Therefore, the economic potential of this style of mineralization is along the strike of the gabbro.

Big Pond (Blue Peter)

Spectacular gold mineralization was discovered at Big Pond (Blue Peter, Figure 1) in 1988 by Noranda. The prospect has been trenched and three diamond-drill holes have been completed. The gold is hosted by a shallow-dipping, northeast-striking, dilational quartz vein (main vein), which is developed within Fe-carbonate altered, sericitized and weakly silicified gabbro (Figure 5). The gabbro, which is fine to medium grained and black, intrudes maroon and green siltstone and sandstone of the Botwood Group. A number of these small gabbro bodies are developed along strike.

The main vein (Figure 6) appears to be part of a sheet-like set of quartz veins, three of which are exposed in the trench. The other two veins are much narrower, more discontinuous and to date have not yielded visible gold. The main vein is exposed for approximately 8 m and exhibits pinch-and-swell structures. It has a maximum thickness of 20 cm and appears to be slightly cupped shaped, plunging to the north-northwest. Abundant pyrite, fine-grained, semi-massive arsenopyrite and locally, coarse free gold are present along the length of the vein. The main vein contains abundant, locally rounded, wall rock and vein fragments, suggesting multiple injections of the mineralizing fluid.

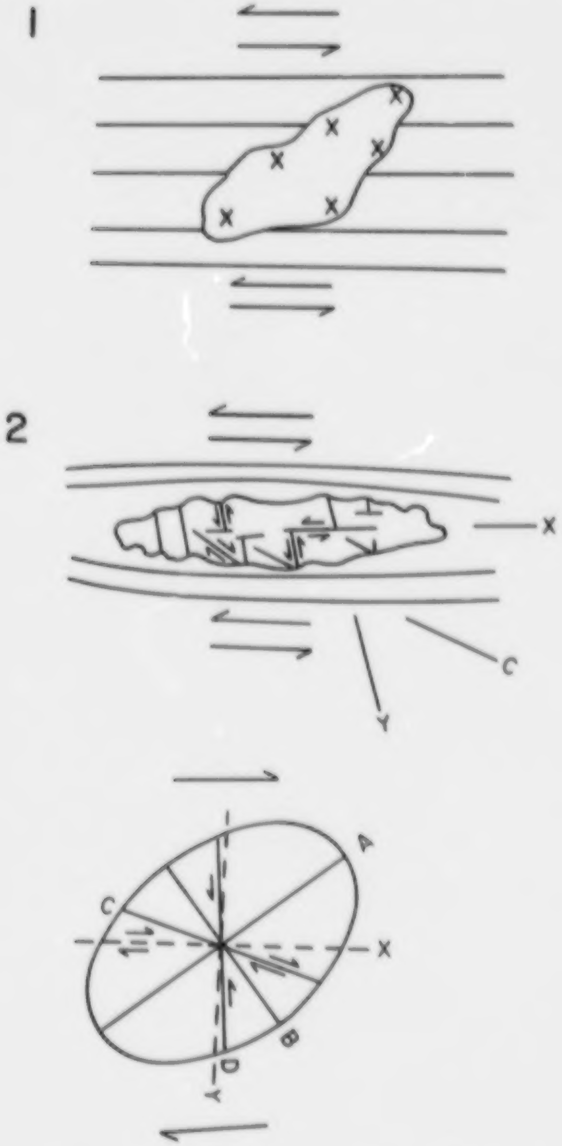


Figure 4. *Generalized model for the development of the structures hosting gold mineralization at Clutha.*

Later, north-northwest and west-northwest trending, small 1- to 2-cm-thick quartz veins transect the north-northeast trending veins. A conjugate set of narrow, brittle shears, which trend north-northwest and east-northeast, locally control quartz veining.

The host gabbro appears to have been intruded close to the intersection of two regionally extensive topographic linears, which are interpreted to be faults. The gabbro has a sigmoidal shape (as projected from drill core), which suggests it was rotated during movement along the fault system producing dilational zones that formed the loci for the mineralizing fluids.

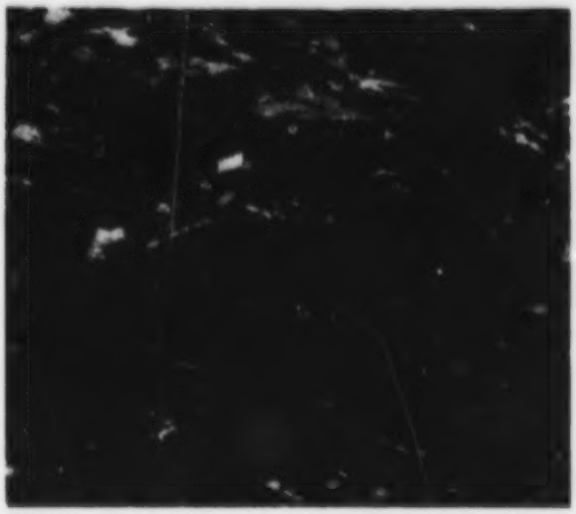


Plate 1. *Quartz veining developed within a conjugate Riedel shear; host rock is deformed and carbonate altered medium-grained gabbro. Note quartz veining developed parallel to the regional cleavage.*

Plate 2. *Blocky alteration and quartz veining (Trench 12). Shearing, alteration and quartz veining follow jointing developed within the gabbro; blocks are remnants of less altered gabbro.*

Jonathans Pond

Gold mineralization was first discovered in the Jonathans Pond (Figure 1) area by the Newfoundland Department of Mines and Energy (Blackwood, 1979, 1982). The gold, which assayed 6 g/t, was described as being associated with pyrite- and arsenopyrite-bearing quartz veins developed within intensely sheared gabbro of the Gander River complex. The veins were described as containing local concentrations of massive pyrite, arsenopyrite and cubic pyrite, and rhombic arsenopyrite crystals 2 to 5 mm across.

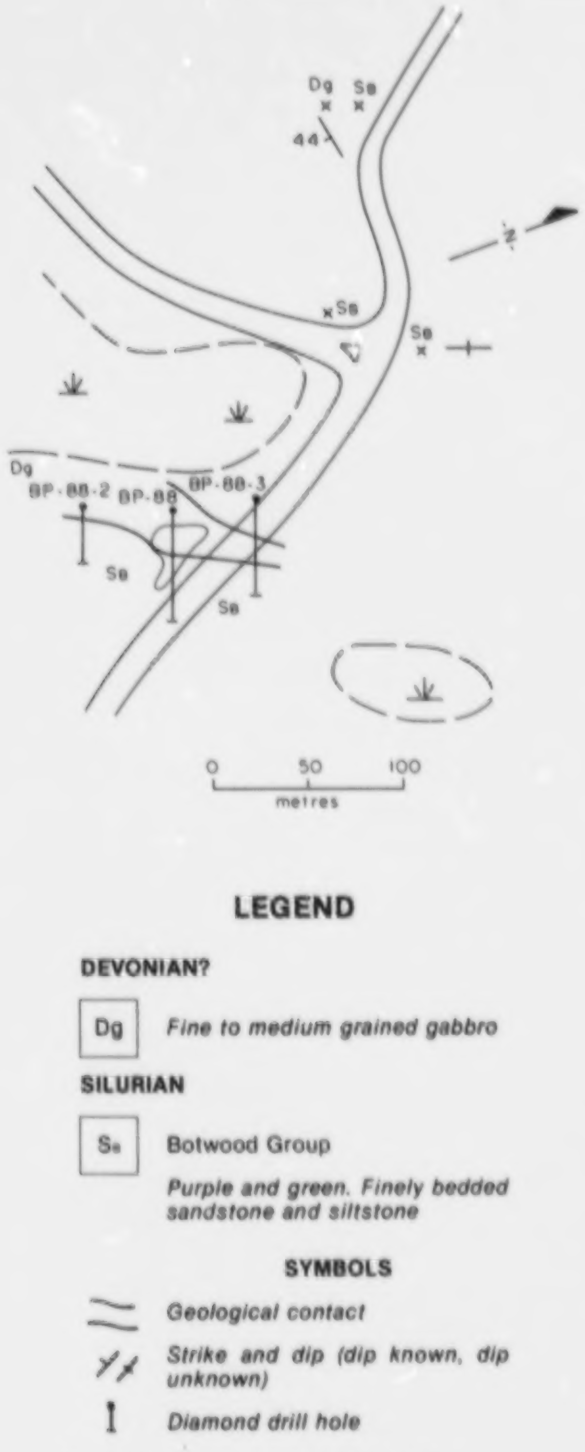


Figure 5. *Geology map of the Big Pond area.*

The area was staked by Westfield Minerals Limited in 1980 (Gagnon, 1981). The company conducted soil- and stream-sediment sampling, mapping, prospecting, trenching and carried out EM-16 surveys. The area was staked by Noranda in 1984 after a regional till-sampling program outlined anomalous gold values (MacKenzie, 1985). Noranda has conducted extensive work on the property but have been hindered by extensive, thick overburden and limited exposure.

The gold mineralization occurs in shear-zone controlled, pyrite- and arsenopyrite-bearing, milky white, locally vuggy quartz veins. The veins, up to 15 cm thick, form a stockwork-like network concentrated in a zone approximately 3 m wide. Pyrite and arsenopyrite within the quartz veins are generally fine grained and disseminated, but coarse sulphides are developed locally. Minor to intense silicification and minor carbonate alteration accompanies the quartz veining.

The gabbro is fine to medium grained and forms part of the Ordovician (?) Gander River complex. Rocks of the complex have been subjected to greenschist-facies metamorphism and as a result chlorite and epidote are common. A weak north-northeast penetrative fabric is developed in the gabbro. Serpentinized and talc–carbonate altered ultramafic rocks are exposed in a trench to the north, and are interpreted to be in fault contact with the gabbro. The setting of this mineralization maybe analogous to the listwaenite model of Buisson and LeBlanc (1985).

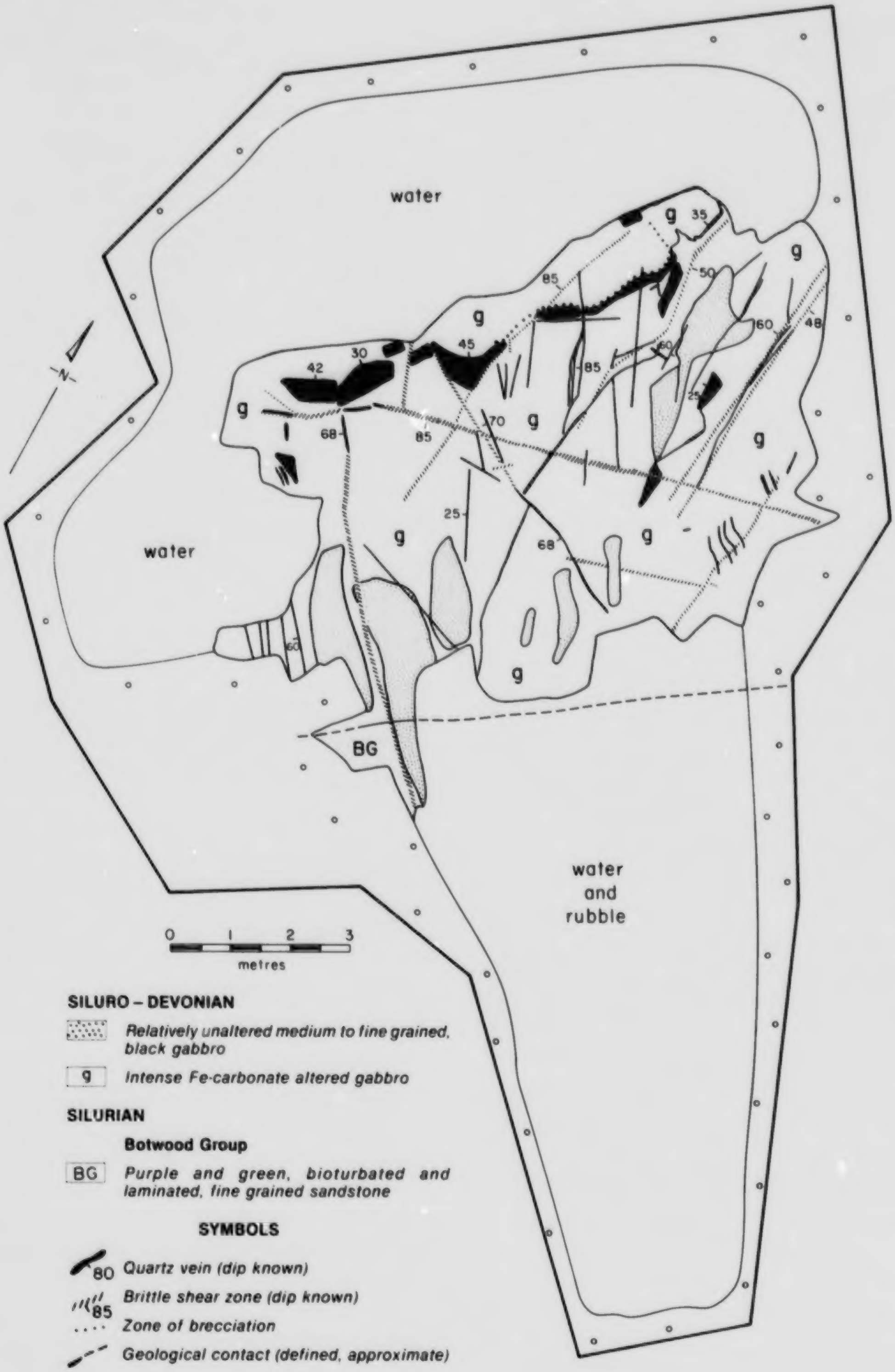
Type 2

Stinger

Sediment-hosted gold-bearing quartz–carbonate veins accompanied by intense silicification and carbonate alteration are developed at the Stinger prospect, Duder Lake (Figure 1). The prospect was discovered by Noranda and is part of an active exploration project in the Duder Lake area. The mineralization, as exposed on surface, comprises a 5- to 10-m-wide zone of fine-grained, highly deformed, silicified and Fe-carbonate altered, slightly graphitic sediments of the Davidsville Group. Dilational, pyrite- and arsenopyrite-bearing quartz–carbonate veins up to 40 cm thick are developed in the zone. Angular, wall-rock fragments are common in the quartz veins. The prospect appears to be a shear-controlled quartz vein system; however, further work is required.

Types 3 and 4

Extensive quartz veining is developed in the slates of the Davidsville Group, particularly to the east of the Gander River. Milky-white, barren quartz veins that developed parallel to the cleavage, and largely parallel to bedding, appear to be metamorphic in origin. Shear-zone hosted gold-bearing quartz–carbonate veins developed in the same rocks, generally, have anomalous gold values. These veins are typically accompanied by minor carbonate alteration that is restricted to the shear zone. The rocks that host the gold-bearing veins are typically graphitic shales and greywackes. Dilational quartz veins carrying gold are developed in deformed greywacke units. The veins developed as a result of rheological differences between the greywacke and surrounding shale.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30
45
68
85
70
25
68
60
25
water
BG
water
and
rubble
0 1 2 3
metres
SILURO – DEVONIAN
Relatively unaltered medium to fine grained, black gabbro
g Intense Fe-carbonate altered gabbro
SILURIAN
Botwood Group
BG Purple and green, bioturbated and laminated, fine grained sandstone
SYMBOLS
80 Quartz vein (dip known)
85 Brittle shear zone (dip known)
Zone of brecciation
Geological contact (defined, approximate)

Figure 6. *Trench map, Big Pond, showing orientations of quartz veining and structures that locally control the veining. The main mineralized vein is located near the northwest edge of the outcrop.*

Bullet

Spectacular gold mineralization was discovered at the Bullet prospect (Figure 1) in 1987 by Noranda. The prospect has been trenched and three diamond-drill holes have been completed. The gold mineralization comprises a narrow, quartz–carbonate vein set (Figure 7) developed within a northeast-trending, steeply south-dipping, dextral shear zone. The quartz veins are generally less then 10 to 15 cm thick and comprise milky-white quartz containing disseminated pyrite, arsenopyrite and minor base metals (Plate 3). The gold occurs as specks and clusters of free gold.

The shear zone, which has a maximum width of 50 cm and an exposed strike length of 24 m, cuts highly cleaved, slightly graphitic shales and siltstone of the Davidsville Group (Figure 8). The shear zone dies out quickly toward the northeast. To the southwest, the shear and quartz veining is offset approximately 1 m by a sinistral shear zone. Movement along this zone appears to have been coincident with quartz-vein development as the vein cuts this shear, was offset by, and folded, into the plane of the shear. There appears to have been late movement on the shear, which hosts the main quartz veins, as these veins are broken and reoriented (Figure 8).

Bowater

The Bowater prospect (Figure 1), discovered by Noranda in 1987, comprises pyritiferous quartz veins and quartz breccia developed within graphitic, locally sericitic, black greywacke. The prospect has been trenched and drilled. Generally, gold assays from the conglomerate are less then 3 g/t (P. Tallman, personal communication, 1990). The greywacke, part of a sequence of graphitic siltstone, pyritiferous shales and greywacke belonging to the Davidsville Group, contains abundant broken feldspar crystals, small glassy quartz grains and sedimentary rock clasts. The sequence contains a slaty cleavage, co-planar to bedding, that trends north-northeast and dips shallowly to the east. Conjugate kink bands and open to moderately tight, southeast-plunging folds, which fold the cleavage, are locally developed (Woldeabzghi, 1988).

The quartz veining is dilational and not restricted to the greywacke. However, the intensity and width of the veining is greater in the greywacke, reflecting the rheological difference between the greywacke and the shales. The veins are typically milky white, locally rusty and vuggy and up to 10 cm in thickness. Minor, narrow, shear-related quartz are locally developed.

A northeast-trending, shallow, southeast-dipping shear zone is developed in the shales exposed in the pit wall approximately 50 m north of the prospect. Associated with this shear are sheeted, rusty quartz veins up to 5 cm thick. These veins appear to be largely restricted to the hanging wall. Samples from these veins will be assayed for gold.

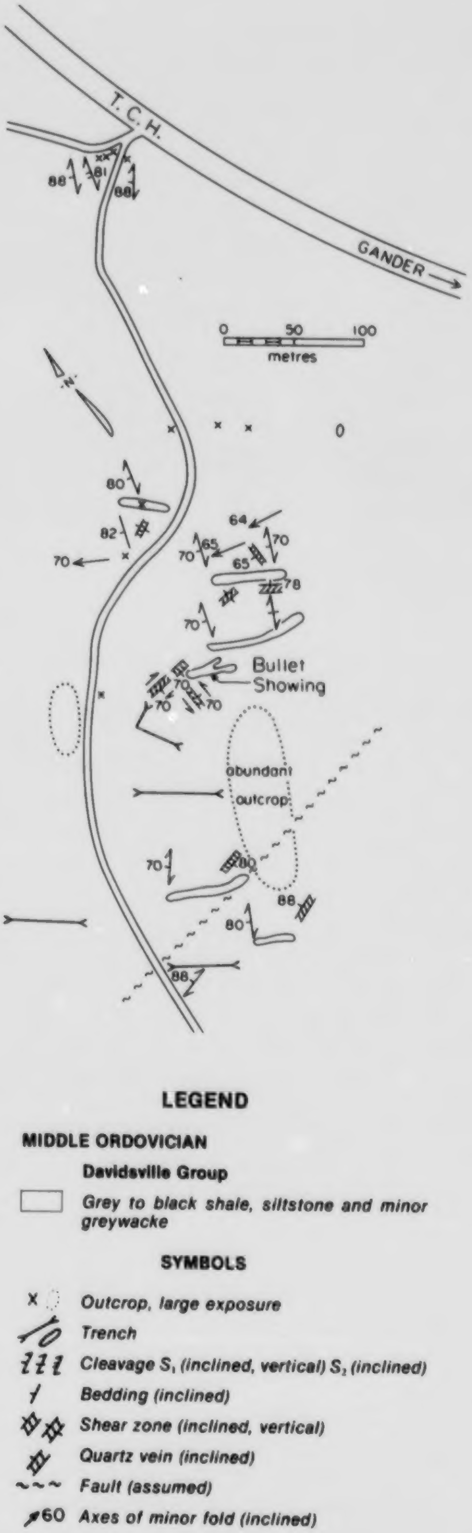
T.C.H.
GANDER
0 50 100
metres
88
81
88
80
82
70
64
65
70
65
78
70
Bullet
Showing
70
70
70
abundant
outcrop
70
80
88
80
88
LEGEND
MIDDLE ORDOVICIAN
Davidsville Group
Grey to black shale, siltstone and minor greywacke
SYMBOLS
Outcrop, large exposure
Trench
Cleavage S₁ (inclined, vertical) S₂ (inclined)
Bedding (inclined)
Shear zone (inclined, vertical)
Quartz vein (inclined)
Fault (assumed)
60
Axes of minor fold (inclined)

Figure 7. *Geology of the Bullet area.*

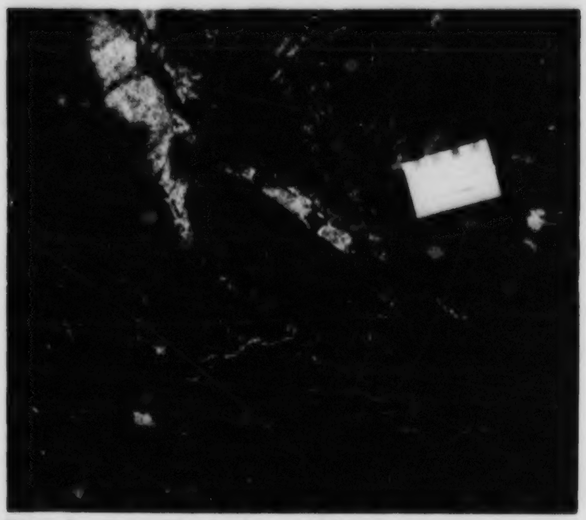

Plate 3. *Sheet-like, broken gold-bearing quartz-carbonate veins developed in a 30-cm-wide shear zone, which cuts highly cleaved Davidsville Group shale.*

Epithermal-Style Mineralization

Epithermal-style, low-grade gold mineralization developed within spectacular hydrothermal breccias occur in sedimentary rocks of both the Davidsville and Botwood groups. This style of mineralization and alteration has only been documented from the rocks south of Glenwood.

The Outflow

Gold mineralization was discovered at The Outflow (Figure 1) in 1987 by Noranda prospectors. Detailed mapping, trenching and diamond-drilling, by Noranda, has outlined anomalous mineralization over a strike length of 5 km. The mineralization is developed within greywacke lenses that are part of a sequence of shale, siltstone, sandstone, greywacke and minor conglomerate of the Davidsville Group (Figure 9). Gower and Tallman (1988) described the sequence as being isoclinally folded with an associated strongly developed penetrative cleavage, which has been deformed by upright to slightly inclined open folding. North-trending brittle faults cut the sequence.

Two mineralized zones, termed the Mustang and Piper zones having strike lengths of 1.8 km and 750 m, respectively, have been outlined (Gower and Tallman, 1988). The gold is associated with pyrite, arsenopyrite, stibnite and intense silicification.

Three styles of related silicification have been documented (Gower and Tallman, 1988): 1) spectacular hydrobreccia stockwork (Plate 4); 2) pervasive silicification; and 3) massive crystalline quartz and quartz–carbonate veins. They have shown that the Mustang Zone comprises all three styles of silicification and contains <1 to 3 percent stibnite

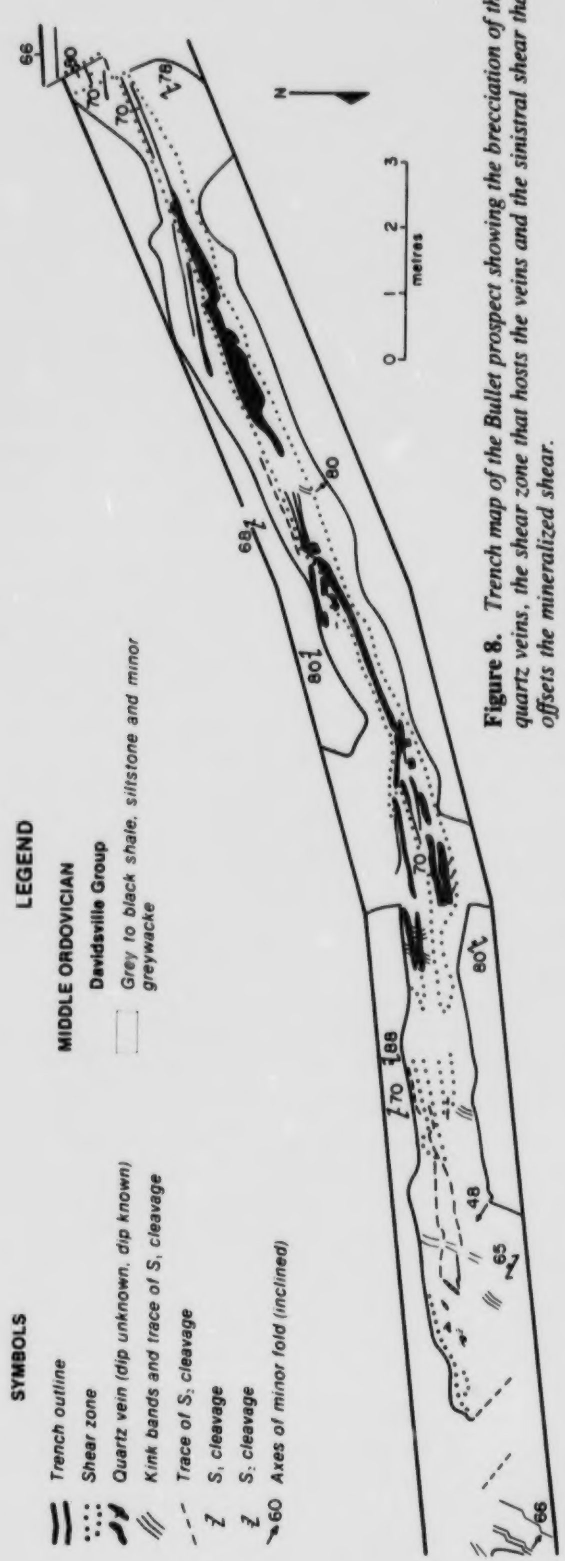
LEGEND
MIDDLE ORDOVICIAN
Davidsville Group
Grey to black shale, siltstone and minor greywacke
SYMBOLS
Trench outline
Shear zone
Quartz vein (dip unknown, dip known)
Kink bands and trace of S1 cleavage
Trace of S2 cleavage
S1 cleavage
S2 cleavage
60 Axes of minor fold (inclined)
N
0
1
2
3
metres
66
30
70
70
78
80
68
80
70
80
88
70
48
65
66

Figure 8. *Trench map of the Bullet prospect showing the brecciation of the quartz veins, the shear zone that hosts the veins and the sinistral shear that offsets the mineralized shear.*

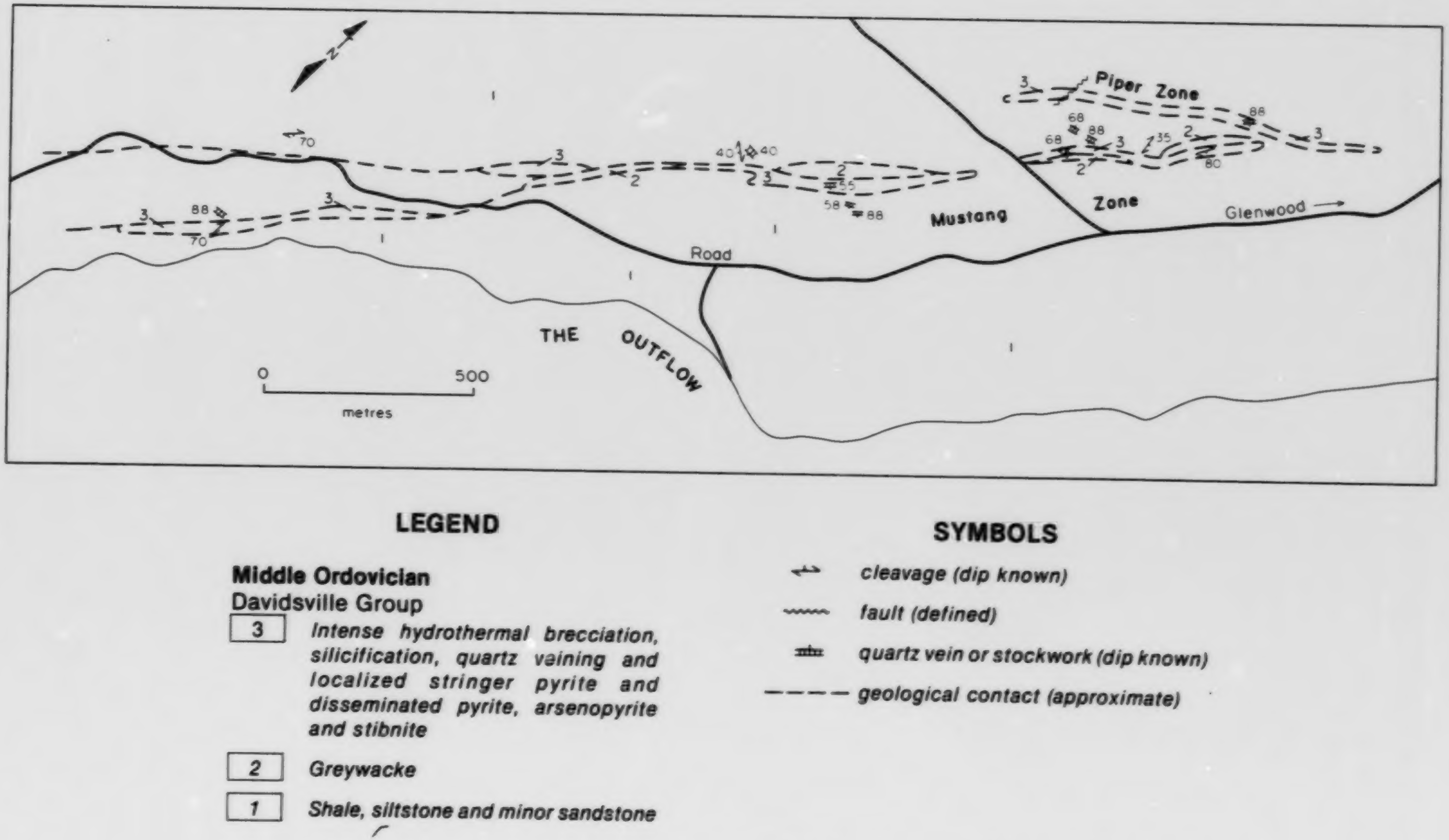
N
70
3
2
40
40
2
35
58
88
Piper Zone
68
88
3
35
2
80
Mustang
Zone
Glenwood →
88
Road
THE OUTFLOW
0
500
metres
1
LEGEND
Middle Ordovician
Davidsville Group
3 Intense hydrothermal brecciation, silicification, quartz veining and localized stringer pyrite and disseminated pyrite, arsenopyrite and stibnite
2 Greywacke
1 Shale, siltstone and minor sandstone
SYMBOLS
cleavage (dip known)
fault (defined)
quartz vein or stockwork (dip known)
geological contact (approximate)

Figure 9. *Geology of The Outflow area (modified after Gower and Tallman, 1988).*

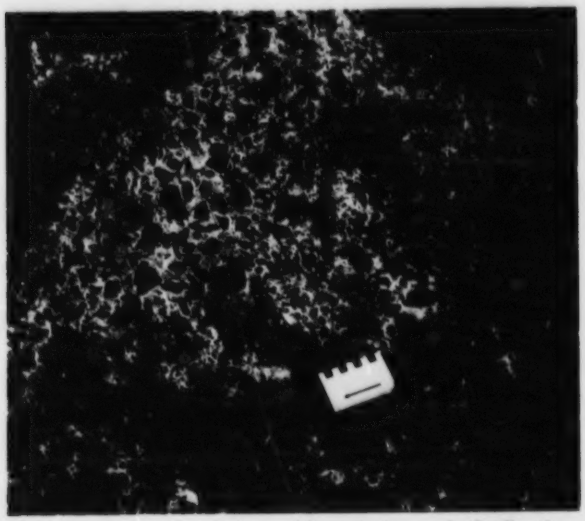

Plate 4. *Intense hydrothermal brecciation and silicification, The Outflow.*

and pyrite; further intense hydrobrecciation, quartz veining and local pervasive silicification characterize the Piper Zone.

Both zones trend northeast-southwest and dip to the northwest. However, the Mustang Zone appears to dip to the southeast at its southwest end (Gower and Tallman, 1988). A channel sample from the Mustang Zone assayed 12.23 g/t gold; gold values are typically <1 g/t (Gower and Tallman, 1988). Gold values for the Piper Zone are typically <1 g/t.

Textures such as the intense hydrobrecciation and vuggy quartz veining observed at The Outflow suggest high-level mineralizing processes more akin to epithermal systems. Tallman (1990) suggested that the relatively high concentrations of stibnite associated with The Outflow prospect may indicate that it formed in the higher levels of a hydrothermal system, which at deeper levels may have developed antimony mineralization similar to the Hunan and related prospects.

Aztec

Epithermal-style (Tallman, 1989a), low-grade gold mineralization was discovered by Noranda in the Paul's Pond area in 1988 (Aztec, Figure 1). The prospect has been trenched and six diamond-drill holes completed. The alteration system was described as being developed at or near the presumed fault contact between the Davidsville and Botwood groups (Figure 10). The fault is described by Tallman (1989b) as a brittle, low-angle thrust, defined by a 10-m-thick graphitic gouge zone, which dips shallowly to the northwest. This fault has been traced for approximately 15 km to the north.

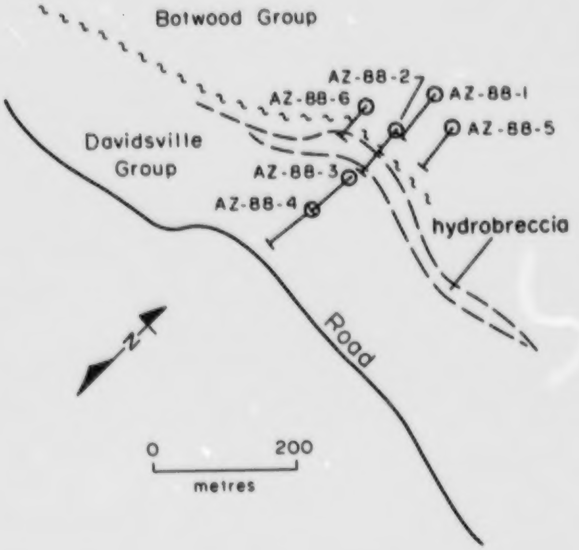

Figure 10. *Geology of the Aztec prospect, showing diamond-drill hole location. (modified after Tallman, 1989b).*

The alteration associated with the Aztec prospect is developed in the structural footwall of this fault zone (Figure 11). The structural footwall to the fault consists of a locally silicified, pyritic conglomerate or breccia. The breccia overlies (but may also be developed adjacent to) the zone described as a silica sinter by Tallman (1989b). Fragments within the conglomerate are locally silicified, suggesting that the unit may have developed in part as talus breccia on the flanks of the sinter. The gold mineralization, typically <1 g/t, is associated with the conglomerate.

Spectacular hydrothermal breccias exhibiting multiple phases of brecciation and pervasive silicification comprise the silica sinter. Breccia fragments exhibit cockade textures comprising concentric rinds of chalcedony. Chalcedony also forms a large portion of the breccia matrix. This unit has a thickness of approximately 10 m and is well exposed on surface.

Structurally beneath this sinter is a 70-m-thick zone of variably developed argillic alteration, developed in fine-grained siltstone and sandstone. The intensity of the alteration appears to decrease downwards, but diamond-drilling did not extend into totally unaltered rocks. On the surface, the alteration has a strike length of 330 m, a width of 100 m and dips shallowly to the northwest (Tallman, 1989b).

The alteration and textures observed at the Aztec prospect fit an epithermal mineralization model related to movement along a regionally extensive structure.

DISCUSSION

Preliminary work indicates that the gold mineralization developed within rocks of the northeastern Dunnage Zone are structurally controlled and epigenetic. The prospects fall into two broad classes—epithermal and the deeper level mesothermal quartz vein systems. Mesothermal gold

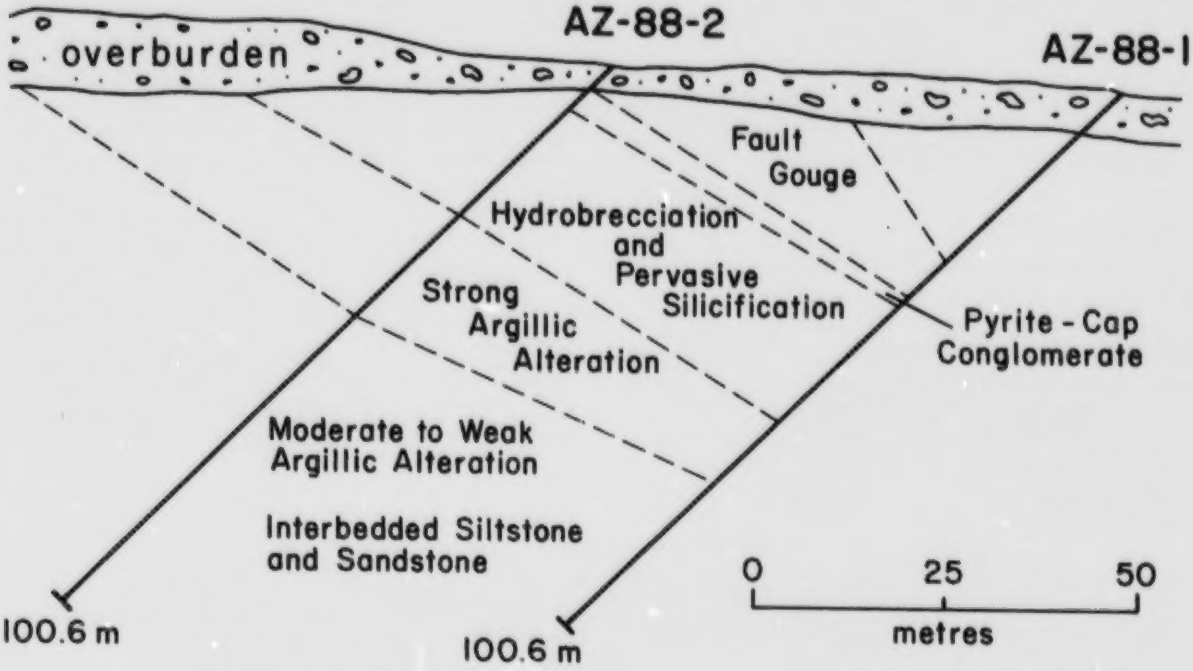

Figure 11. *Schematic cross-section through the Aztec prospect (modified after Tallman, 1989b).*

mineralization is tentatively subdivided into four types or styles based on variations in deposit style and host-rock characteristics.

Certain characteristics are shared by both the epithermal and mesothermal gold occurrences. They are all spatially associated with, and have been structurally modified by, fault systems of regional extent. The actual site and style of the gold mineralization is controlled largely by rheological differences between the host rock and the surrounding rocks.

Many of the variations or differences between the individual mesothermal prospects can be explained by the degree of disequilibrium between the host rocks and the ore fluids. Fe-rich rocks (those with a high Fe/(Fe+Mg) ratio; Barley and Groves, 1990) and graphitic sediments (Colvine *et al.*, 1984) appear to be selectively mineralized. Therefore, when a favourable, structurally prepared rock unit is subjected to mineralizing fluids, a gold-bearing quartz vein system may develop.

The gabbro bodies are Fe-rich and rheologically ideal for the formation of either shear-zone hosted or dilational, mesothermal quartz veins. Therefore, the numerous gabbro plugs may prove to be the best exploration targets as they exhibit the most favourable characteristics for the development of economic concentrations of gold mineralization. There appears to be a preponderance of small gabbroic bodies developed within the Middle Ordovician sedimentary sequences of the Exploits (B. O'Brien, personal communication, 1990), Victoria Lake and Davidsville groups. The regional geological significance of this phenomena is not clear. However, it has significant regional implications for mineral exploration as the sedimentary sequences of the Victoria Lake and Exploits groups are largely unexplored for gold.

Alteration and gold mineralization within the northeastern Dunnage Zone appears to be localized along second or higher order structures that form a complex network of northeast-, north-northeast- and northwest-trending linears. Figure 1 shows a regional, structural, linear map based on orthophoto interpretation. A similar regional model for gold mineralization has been suggested for the Victoria Lake Group (Kean and Evans, 1988; Evans *et al.*, 1990). These structures are related to a late accretionary transpressive regime active during the Late Silurian and early Devonian. Such regimes would be characterized by relatively high heat flow, a network of deep level structures, which would act as fluid pathways, and abundant high concentrations of H_2O- and C_2O-rich fluids (Kerrich, 1989; Kerrich and Wyman, 1990; Barley and Groves, 1990).

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REFERENCES

Anderson, F.D. and Williams, H.
1970: Gander Lake (west half), Newfoundland. Geological Survey of Canada, Map 1195A (geological map and descriptive notes).

Baird, D.M.
1958: Fogo Island map area, Newfoundland (2E/9, mainly). Geological Survey of Canada, Memoir 301, 43 pages.

Baird, D.M., Moore, J.G.G., Scott, H.S. and Walker, W.
1951: Reconnaissance geology of east central Newfoundland between Sir Charles Hamilton Sound and Baie d'Espoir. Department of Natural Resources, Mineral Development Division, Newfoundland Geological Survey, unpublished report, 155 pages. [Nfld (73)]

Barley, M.E. and Groves, D.I.
1990: Mesothermal gold mineralization in the Yilgarn Craton, Western Austrailia, the result of late Archaean convergent tectonics? Chronique de la recherche miniere, Number 498, pages 3-13.

Blackwood, R.F.
1979: Geology of the Gander River area (2E/2) Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 79-1, pages 38-42.

1981: West Gander Rivers (east half) and Dead Wolf Pond (northwest portion). Newfoundland Department of Mines and Energy, Mineral Development Division, Map 81-100 (geology map and descriptive notes).

1982: Geology of the Gander Lake (2D/15) and Gander River (2D/2) area. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-4, 56 pages.

1983: Dead Wolf Pond (2D/10), Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 82-70 (geology map and descriptive notes).

Buisson, G. and Leblanc, M.
1985: Gold in carbonatized ultramafic rocks from ophiolite complexes. Economic Geology, Volume 80, pages 2028-2029.

Colman-Sadd, S. and Swinden, H.S.
1984: A tectonic window in Central Newfoundland? Geological evidence that the Appalachian Dunnage Zone may be allochthonous. Canadian Journal Earth Sciences, Volume 21, pages 1349-1357.

Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, A.J., Lavigne, M.J., Jr., MacDonald, A.J., Marmont, S., Poulsen, K.H., Springer, J.S., and Troop, D.G.
1984: An integrated model for the origin of Archean lode gold deposits. Ontario Geological Survey Open File Report 5524, 98 pages.

Coyle, M. and Strong, D.F.
1987: Geology of the Springdale Group: a newly recognized Silurian epicontinental-type caldera in Newfoundland. Canadian Journal of Earth Sciences, Volume 24, pages 1135-1148.

Currie, K.L., Pajari, Jr., G.E. and Pickerill, R.K.
1980: Geological map of Carmanville map area (2E/8), Newfoundland. Geological Survey of Canada, Open File 721, map with descriptive notes.

Davenport, P.H. and Nolan, L.W.
1988: Gold and associated elements in lake sediment from regional surveys in the Botwood map area (NTS 2E). Newfoundland Department of Mines, Mineral Development Division, Open File 2E/563.

Davenport, P.H., Nolan, L.W. and Hayes, J.P.
1988: Gold and associated elements in lake sediment from regional surveys in the Gander Lake map area (NTS 2D). Newfoundland Department of Mines, Geological Survey Branch, Open File 2D/175.

Dunlop, W.B.
1955: Evaluation of the area between Gander Lake and Sir Charles Hamilton Sound. Newfoundland and Labrador Corporation Limited, unpublished report, 6 pages. [2E (71)]

Evans, D.T.W., Kean, B.F. and Dunning, G.R.
1990: Geological studies, Victoria Lake Group, central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 131-144.

Gagon, J.
1981: Report on the geological, geochemical and geophysical exploration. Jonathans Pond claims, Gander area. Westfield Minerals Limited, unpublished report, 10 pages. [2E/2 (410)]

Gower, D. and Tallman, P.
1988: Second year assessment report on geological mapping, prospecting, trenching, soil geochemistry, geophysical surveys and diamond drilling at Gander Outflow. Noranda Exploration Company Limited, confidential report, 16 pages. [2D/15 (198)]

Jenness, S.E.
1954: Geology of the Gander River Ultrabasic Belt, Newfoundland. Unpublished Ph.D. thesis, Yale University, New Haven.

1958: Geology of the Gander River Ultrabasic Belt, Newfoundland. Geological Survey of Newfoundland, Report 11, 58 pages.

1963: Terra Nova and Bonavista Bay map areas, Newfoundland. Geological Survey of Canada, Memoir 327, 184 pages.

Kean, B.F. and Evans, D.T.W.
1988: Regional metallogeny of the Victoria Lake Group, central Newfoundland. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 319-330.

Kennedy, M.J.
1975: Repetitive orogeny in the northeastern Appalachians–new plate models based on Newfoundland examples. Tectonophysics, Volume 28, pages 39-87.

Kennedy, M.J. and McGonigal, M.H.
1972: The Gander Lake and Davidsville Groups of northeastern Newfoundland: new data and geotectonic implications. Canadian Journal of Earth Sciences, Volume 9, pages 452-459.

Kerrich, R.
1989: Geodynamic setting and hydraulic regimes: shear hosted mesothermal gold deposits. *In* Mineralization and Shear Zones. *Edited by* J. Bursnall. Geological Association of Canada, Short Course Notes, Volume 6, pages 89-128.

Kerrich, R. and Wyman, D.
1990: Geodynamic setting of mesothermal gold deposits: an association with accretionary tectonic regimes. Geology, Volume 18, pages 882-885.

MacKenzie, A.C.
1985: First year assessment report (geological, geophysical and geochemical) licence 2472. Noranda Exploration Company Limited, confidential report, 19 pages. [2E (532)]

Murray, A. and Howley, J.P.
1881: Geological Survey of Newfoundland. Edward Stanford, London, 536 p.

Noront Resources Limited
1990: Progress report to shareholders, September 12, 3 pages.

O'Neill, P.
1987: Geology of the west half of the Weir's Pond (2E/1) map area. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 271-281.

1990: Geology of the northeast Gander Lake map area (NTS 2D/15) and the northwest Gambo map area (NTS 2D/16). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 317-326.

O'Neill, P. and Blackwood, R.F.
1989: A proposal for revised stratigraphic nomenclature of the Gander and Davidsville groups and the Gander River Ultrabasic Belt, of northeastern Newfoundland. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 127-130.

O'Neill, P. and Knight, I.
1988: Geology of the east half of the Weir's Pond (2E/1) map area and its regional significance. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 165-176.

Patrick, T.O.H.
1956: Comfort Cove, Newfoundland. Geological Survey of Canada, Paper 55-31 (geological map with marginal notes).

Snelgrove, A.K.
1934: Chromite deposits of Newfoundland. Department of Natural Resources, Newfoundland, Bulletin #1, 26 pages.

Swinden, H.S.
1990: Regional geology and metallogeny of central Newfoundland. *In* Metallogenic framework of base and precious metal deposits, central and western Newfoundland. *Edited by* H.S. Swinden, D.T.W. Evans and B.F. Kean. Eighth IAGOD Symposium Field Trip Guidebook. Geological Survey of Canada, Open File 2156, pages 1-27.

Szybinski, Z.A., Swinden, H.S., O'Brien, F.H.C., Jenner, G.A. and Dunning, G.R.
1990: Correlation of Ordovician volcanic terranes in the Newfoundland Appalachians: lithological, geochemical and age constraints (abstract). Geological Association of Canada, Program with Abstracts, Volume 15, page A128.

Tallman, P.
1989a: First year assessment report on Licence 3418 Noront-Paul's Pond (4716) NTS 2D/11. Noranda Exploration Company Limited, confidential report, 5 pages. [2D/11 (204)]

1989b: First year assessment report on Licences 3361, 3468, 3536, 3480, 3418, 3547, 3539, 3549, 3537, 3538, 3559, NTS 2D/11. Noranda Exploration Company Limited, confidential report, 19 pages. [2D/11 (221)]

1990: Exploration results from the 'Hunan' antimony discovery in central Newfoundland. Program with Abstracts, Canadian Institute of Mining and Metallurgy, Seventh District One Annual Meeting, St. John's, Newfoundland, pages 11-12.

Twenhofel, W.H.
1947: The Silurian of eastern Newfoundland with some data relating to physiography and Wisconsin glaciation of Newfoundland. American Journal of Science, Volume 245, pages 65-122.

Twenhofel, W.H. and Shrock, R.R.
1937: Silurian strata of Notre Dame Bay and Exploits Valley, Newfoundland. Geological Society of America Bulletin, Volume 48, pages 1743-1772.

Williams, H.
1964: Botwood, Newfoundland. Geological Survey of Canada, Map 60-1963 (geological map and descriptive notes).

1979: Appalachian Orogen in Canada. Canadian Journal of Earth Sciences, Volume 16, pages 792-807.

Woldeabzghi, T.
1988: 1987 exploration program, Glenwood-White Bay property Project Number 4125 Licence 2821 NTS 2D/15. Noranda Exploration Company Limited, confidential report, 18 pages. [2D/15 (186)]

NOTE: Geological Survey Branch file numbers are included in square brackets.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 319-326

LIMESTONE ASSESSMENT ON NEWFOUNDLAND'S GREAT NORTHERN PENINSULA

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Mineral Deposits Section

ABSTRACT

An assessment of limestone prospects was carried out in the Pistolet Bay and Canada Bay regions of the Great Northern Peninsula. The deposits are found mainly, but not exclusively, in the Middle Ordovician Table Head Group. The purpose of the survey was to identify industrial-grade limestone suitable for a range of applications including cement and lime manufacturing, as well as use in the current high-growth areas of aggregate and environmental clean-up. The most promising prospect (Burnt Island) is a large, readily accessible deposit that underlies a peninsula adjoining the community of Raleigh. Detailed bedrock sampling indicates the deposit to be of exceptional purity. Other deposits of good quality were investigated near Cooks Harbour and in the Canada Bay region.

INTRODUCTION

The lower Paleozoic carbonate sequences of western Newfoundland host important deposits of limestone, marble and dolomite. Current production is confined to limestone deposits located at the southern end of the belt. Producers include the well-established cement-manufacturing plant at Corner Brook (North Star Cement Limited), the newly developed high-volume limestone aggregate quarry at Lower Cove on the Port au Port peninsula (Newfoundland Resources and Mining), and an agricultural limestone quarry at Cormack (Havelock Lime). At the northern end of the belt, industrial attention has focussed on high-purity white-marble deposits in the Roddickton area, where assessment and quarry development have taken place on deposits located near Roddickton and Croque (Aurion Minerals Limited and ECC International Limited). Currently, there is increased interest in the province's limestone resource. This interest stems from a number of factors. These include the successful start-up of the Lower Cove limestone aggregate operation, the imminent start of offshore oil development with its requirement for large volumes of cement, and emerging new uses and markets in pollution control systems. One of the largest growth areas is in the field of environmental clean-up, where most of the techniques being developed to reduce sulphur dioxide emissions, require large amounts of high-purity limestone.

The present study concentrated on deposits of potential commercial interest on the Great Northern Peninsula (Figure 1). Earlier assessments noted the commercial potential of these deposits yet stressed their relative remoteness as a serious impediment to development. General improvements in infrastructure on the Great Northern Peninsula, coupled with a growing recognition of the strategic tidewater location of these deposits, prompted the present survey.

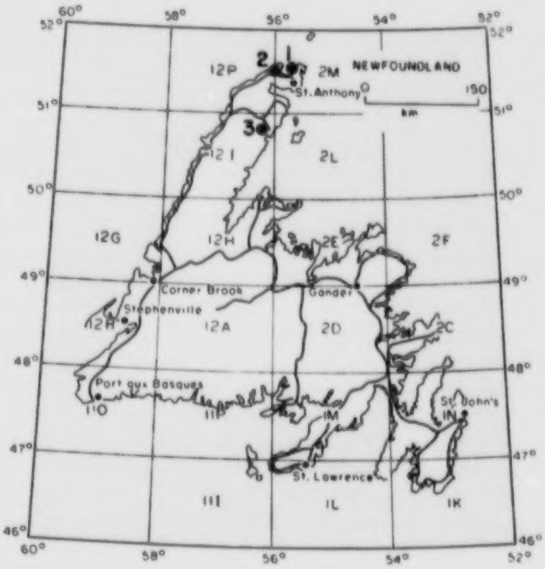

Figure 1. *Location of limestone assessment areas: 1) Raleigh; 2) Cooks Harbour; 3) Canada Bay.*

HISTORY OF LIMESTONE ASSESSMENT AND DEVELOPMENT

The beginning of limestone production in Newfoundland dates back to the early nineteenth century when quarrying on a small scale was carried out in several areas to supply raw material for lime production. Kilns, located in St. John's, were supplied with stone from the thin Cambrian sequences on the Avalon Peninsula, and also with limestone from the higher grade Ordovician deposits at Cobbs Arm. The busy copper mines at Tilt Cove, Betts Cove, and Little Bay also used Notre Dame Bay limestone to provide a neutralizing agent for treating the ore (Harris, 1962).

The limestone industry acquired a more important status in the Newfoundland economy in 1913 when the Dominion Steel and Coal Corporation (DOSCO) established a quarry and loading facility at Aguathuna, on the Port au Port Peninsula. The limestone was shipped to Sydney, Nova Scotia, where it was used as a fluxing agent in the DOSCO steel mills. The Aguathuna operation lasted for 50 years and produced a total of about 10 million tonnes by the time it closed in 1965. The Aguathuna quarries marked the first significant limestone production from the west coast carbonate sequences. Most of the production came from the Middle Ordovician Table Point Formation, although in later years some production came from carbonates of the Lower Ordovician St. George Group.

The start of the pulp and paper industry in Newfoundland introduced a new but rather modest market for limestone. This demand was supplied by the existing quarries at Aguathuna and Cobbs Arm, and the Dormston quarry at Corner Brook. An idea of the scale of production can be seen from statistics that show between 1943 to 1956 Bowaters Pulp and Paper Limited at Corner Brook quarried 15,000 to 20,000 tonnes annually from the Dormston quarry for the manufacture of sulphite pulp.

Shortly after Newfoundland joined Canada in 1949, a cement plant was established in Corner Brook. Operated by North Star Cement Limited, it utilizes nearby deposits of limestone and shale and Flat Bay gypsum to manufacture portland cement. About 80,000 tonnes per year (tpy) are produced for the Newfoundland construction industry.

Beginning in the 1950's, there was an increased recognition of the province's industrial-mineral potential. This was reflected on the west coast by a series of limestone and gypsum studies including reconnaissance limestone surveys by Lee (1956) and Harris (1962), followed by more detailed studies around Corner Brook by Mckillop (1961, 1963), and on the Port au Port Peninsula (Besaw, 1973). The data from these surveys, as well as information from numerous other sources, were incorporated in a comprehensive report on insular Newfoundland's limestone resources by DeGrace (1974).

Involvement by industry in the assessment of Newfoundland industrial carbonates up until very recent times has been minimal. The concession system of the 1950's through to the early 1970's wherein a few large companies, preoccupied with metallic exploration, were given exclusive mineral exploration rights over large areas of the province, contributed to the situation. However, British Newfoundland Exploration Limited (Brinex), the mineral-exploration arm of BRINCO, delineated about 50 million tonnes of high-purity limestone at Coney Arm (Bedford, 1957), and about 200 million tonnes of exceptionally pure stone on the Port au port Peninsula. Brinex (now Western Canadian Mining Corporation), are currently reassessing their Port au Port limestone properties.

PRESENT SURVEY

OBJECTIVES AND PARAMETERS

The purpose of the survey was to identify industrial-grade limestone on the Northern Peninsula. For the purposes of this report, the term industrial refers mainly to cement and metallurgical-grade stone but also includes limestone suitable for use in agriculture, in pollution control systems and as aggregate.

The primary component of limestone, which determines whether or not it is metallurgical grade, is its SiO_2 content, where percentages greater than 2.5 are unacceptable. Magnesium oxide content is not critical if it is predictable, but the Al_2O_3 content should not exceed one percent.

The critical criteria in determining whether limestone is cement grade, is its MgO content, which should not exceed 4 percent. Considerable variation in other elements, particularly silica, aluminum, and iron, can be accommodated because quartzite and shale are commonly added to raw clinker in a cement plant. Among the trace elements, alkali content (K_2O + Na_2O) can be very deleterious if it exceeds a half of a percent.

The physical and chemical parameters of carbonate rocks have been the subject of much research to determine the factors that affect their performance in the environmental field of sulphur emissions and acid rain. With regard to the specifications for limestone used in a gas scrubber, there are certain conditions required in terms of fineness and chemical purity. A high-grade limestone is required, with a maximum 5 percent acid insolubles, although some systems look for higher standards (Power, 1985). Iron content could be beneficial (as a catalyst in the process) but not if it occurs as pyrite, which reduces reactivity. A fine-grained porous stone is favoured although it should be noted that it is the pore size of the calcined rock that is important, rather than that of the raw limestone (Hamer, 1986).

ACCESS AND METHODS

The Viking Highway (Route 73), which connects with the Trans-Canada Highway at Deer Lake, offers paved access to the western side of the Northern Peninsula. Communities around Pistolet Bay, such as Raleigh and Cooks Harbour, are linked to this highway by short all-weather roads (also partly paved or slated for paving). A strategically located regional airport also serves the area's transportation needs, especially the town of St. Anthony, the headquarters of the Grenfell Mission and the region's chief commercial and service centre. A 40-km trans-peninsular gravel road (up-graded for paving) links communities on the eastern side of the peninsula to Route 73. A network of woods roads and other trails most of which are drivable, provide additional access to limestone deposits. Most importantly, the deposits are located on or close to tidewater.

Three major prospects, along with a number of other occurrences, were investigated during the 1990 field season (Figure 1). The limestone beds were systematically chip sampled along lines perpendicular to their strike using a 4 kg sledgehammer and a geology hammer to remove weathered surfaces. Sample sites were plotted on air photographs and 1:50,000-scale NTS map sheets. Approximately 170 samples were collected for analysis at the Newfoundland Department of Mines and Energy geochemical laboratory. In addition, 10-kg representative samples were taken for tests to determine the limestone's suitability as a reagent for flue-gas desulphurization.

LIMESTONE PROSPECTS

RALEIGH (BURNT ISLAND)

One of the most commercially attractive limestone prospects in the province underlies Burnt Island near the community of Raleigh on the east side of Pistolet Bay (Figure 2). Burnt Island is in fact a Peninsula connected by a natural land bridge to Raleigh. A road across this isthmus provides access to all parts of the deposit. The peninsula and Raleigh form a natural harbour that is able to accommodate large ships.

Much of Burnt Island is exposed bedrock consisting of limestone of the Lower Ordovician St. George Group, disconformably overlain by Table Point limestone of the Middle Ordovician Table Head Group. The south and southwest parts of the island are underlain by shales of the Ordovician Goose Tickle Formation. Small, thin deposits of limestone gravels, typical of weathered Table Head formations, are common and these are being exploited locally on a small scale for road aggregate.

On the eastern side of the island, the stone is typical Table Point but is more contorted and recrystallized than other occurrences in the region. The limestone is fine grained, quite hard and contains abundant white calcite veins and stringers. Along sample lines, zones of brecciated limestone and thin argillaceous seams were observed. The argillite is too thin and localized to significantly dilute the overall quality of the stone. The limestone beds are folded in an undulating manner but the average dip is about 10 to 12° eastward.

White and grey limestone and dolomitic limestone of the St. George Group underlies the western side of Burnt Island. This stone is extremely pure and resembles the Catoche limestone (White Hills limestone) on the Port au Port Peninsula. It is estimated to be about 15 m thick. The white limestone is underlain by dolomitic limestone along the western margin of the island.

One of the commercially enhancing features of the deposit is that it is extremely well suited for quarrying. The plateau-shaped peninsula (maximum elevation 75 m) has a pronounced yet easily accessible slope on its harbour side (Plate 1) that would facillitate quarry development. Also, there is almost a complete absence of overburden (Plate 2).

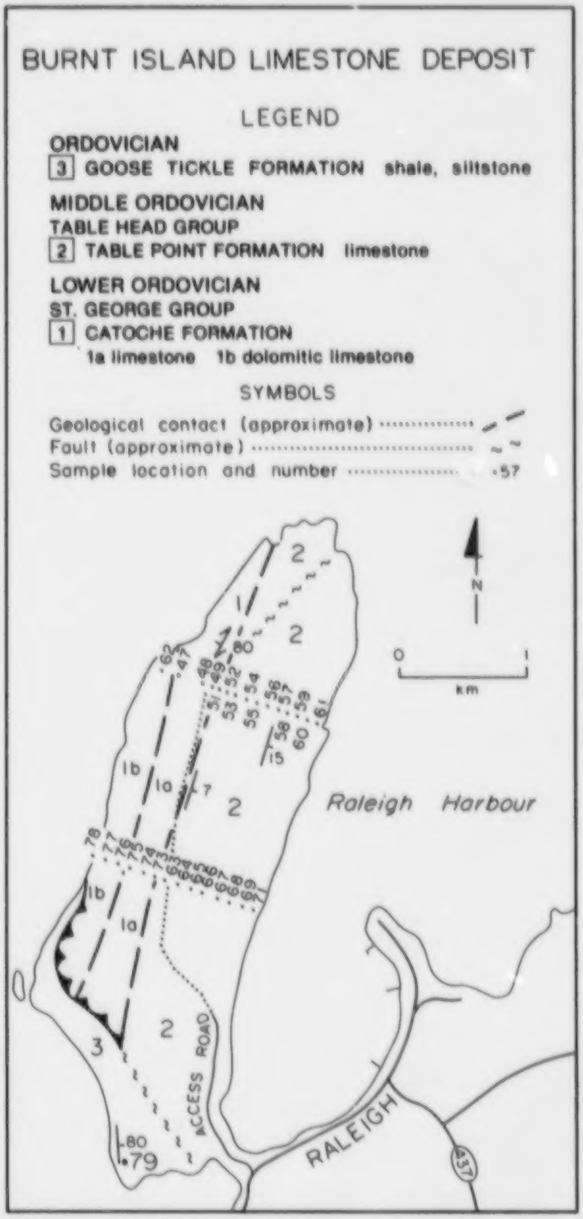
BURNT ISLAND LIMESTONE DEPOSIT
LEGEND
ORDOVICIAN
3 GOOSE TICKLE FORMATION shale, siltstone
MIDDLE ORDOVICIAN
TABLE HEAD GROUP
2 TABLE POINT FORMATION limestone
LOWER ORDOVICIAN
ST. GEORGE GROUP
1 CATOCHE FORMATION
1a limestone 1b dolomitic limestone
SYMBOLS
Geological contact (approximate)
Fault (approximate)
Sample location and number .57
N
0 1
km
Raleigh Harbour
ACCESS ROAD
RALEIGH
437
1a
1b
2
3
80
79

Figure 2. *Location of the Burnt Island–Raleigh limestone deposit. (Geology modified after Knight, 1986a)*

SAMPLING RESULTS AND RESERVE POTENTIAL

Table 1 (a and b) shows the chemical analyses of representative chip samples from the Burnt Island limestone deposit. These results indicate the presence of a large deposit grading around 98 percent calcium carbonate. Silica content is low at just over a quarter of a percent and iron and aluminum add up to 0.11 percent. Magnesium carbonate content is less than one and a half percent. Sodium oxide and K_2O (not shown in Table 1) averaged 160 ppm and 450

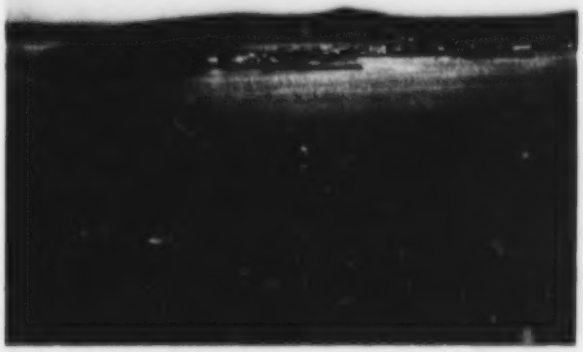

Plate 1. *Burnt Island looking across its eastern slope and across Raleigh Harbour.*

Plate 2. *Burnt Island limestone deposit looking north along strike.*

ppm, respectively. The results support field observations that the deposit is underlain by dolomitic limestone exposed along the western margin of the island (Figure 2). This is reflected in sample 62 and samples 76 to 78, which averaged 28.7 percent magnesian carbonate (Table 1b).

The sampling program indicates a large reserve of quarryable limestone on Burnt Island, a significant proportion of which is of very high quality. A conservative estimate of 150 million tonnes on the middle and eastern half of the island would appear to exceed the specifications for most industrial applications. At present, there is no information available on the limestones's suitability for use as aggregate or in the field of pollution control. However, the low level of impurities, especially silica, suggests the stone may have good aggregate potential.

It should be emphasized that the 1990 assessment sampled limestone bedrock exposed on the surface. This was done in a systematic manner and care was taken to collect unweathered representative samples. However, in order to provide more accurate and definitive information on the size and quality of the deposit, a diamond-drilling program would have to be carried out.

Table 1. a) Chemical analyses for chip samples from the Burnt Island limestone deposit; see Figure 2 for sample locations

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$
47	0.20	0.06	0.02	98.50	0.50
48	0.31	0.15	0.02	98.54	0.67
49	0.24	0.07	0.02	98.48	1.06
51	0.18	0.05	0.01	98.98	0.60
52	0.30	0.06	0.02	98.33	1.00
53	0.26	0.06	0.03	98.06	0.96
54	0.32	0.08	0.02	97.43	2.26
55	0.15	0.04	0.03	97.76	1.02
56	0.31	0.06	0.02	99.31	0.92
57	0.36	0.12	0.04	99.13	1.53
58	0.18	0.06	0.02	99.86	1.19
59	0.23	0.06	0.02	98.24	1.27
61	0.33	0.09	0.03	97.12	2.47
63	0.21	0.07	0.03	98.84	1.11
64	0.34	0.08	0.03	98.38	1.52
65	0.15	0.04	0.01	98.47	1.17
66	0.17	0.06	0.01	99.23	1.29
67	0.18	0.05	0.01	97.33	3.32
68	0.26	0.04	0.04	98.93	1.50
69	0.22	0.05	0.02	97.42	1.92
71	0.45	0.12	0.06	96.69	2.17
72	0.42	0.15	0.06	96.94	1.44
73	0.09	0.04	0.02	99.45	0.40
74	0.23	0.07	0.06	99.50	0.42
75	0.36	0.19	0.07	98.78	0.56
AVERAGE	0.26	0.08	0.03	98.38	1.31

b) Chemical analyses of chip samples from dolomitic limestone on western side of Burnt Island; see Figure 2 for sample locations

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$
62	0.35	0.19	0.11	67.76	31.39
76	0.20	0.08	0.06	72.62	26.88
77	0.69	0.28	0.15	58.19	38.44
78	2.36	0.42	0.14	78.37	18.22
AVERAGE	0.90	0.24	0.12	69.23	28.73

COOKS HARBOUR DEPOSITS

Table Head formations on the west side of Pistolet Bay were also investigated for industrial-grade limestone. The most promising unit, the Table Point Formation, as delineated by Knight (1986a), extends from Cooks Point southward to the old Viking Highway and beyond. Two areas that received the most attention were the Cooks Point area to the immediate north of the community of Cooks harbour, and an inland high-purity limestone zone that intersects the old Viking Highway about 2.5 km west of the Cooks Harbour road junction (Figure 3).

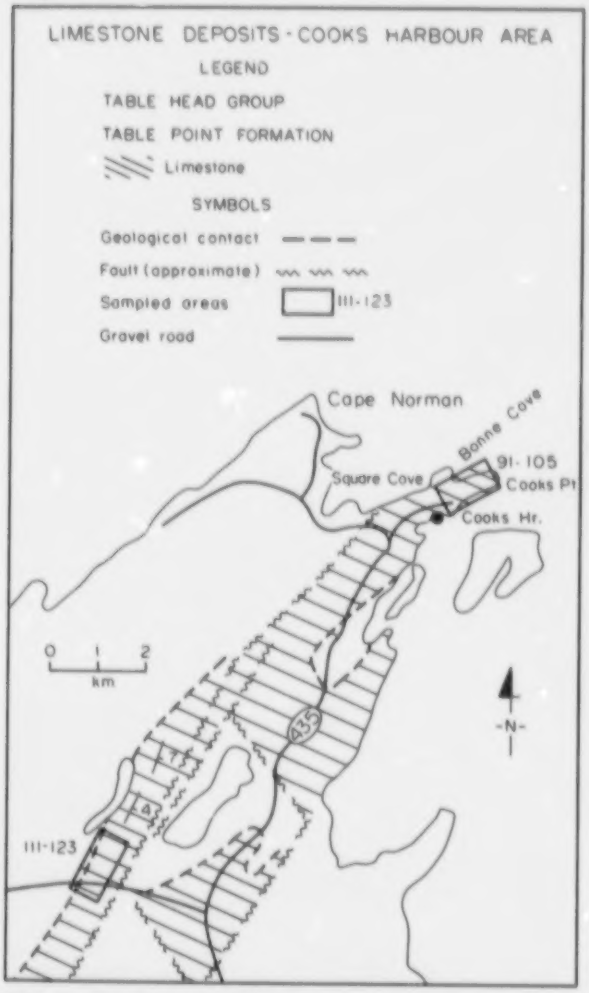

Figure 3. *Location of limestone deposits near Cooks Harbour. (Geology after Knight, 1986a)*

A 4-km strike length of the inland deposit was investigated and sampled. The flat-lying limestone beds (dips average 5° to southeast) are exposed along a low northeast-trending ridge. The limestone has a strongly developed vertical cleavage, which parallels its northeast strike, and in many shattered and jointed areas, weathering has produced a thin covering of limestone gravel. Two lines located approximately a kilometre apart were sampled at 50 m intervals across the width of the formation.

COOKS HARBOUR

The limestone formations that underlie the area between the community of Cooks Harbour and the north coastline have been cited by previous investigators as being particularly well suited for a limestone quarry (e.g., Harris, 1962). However, information was lacking with regard to the quality of the stone because, prior to the present program, virtually no sampling had been carried out.

The limestone is medium dark grey, fossiliferous, containing extensive calcite veining. Sampling encountered minor seams of argillaceous limestone throughout the section from Cooks Point to Square Bay, and zones 20 to 30 cm wide were observed on the east side of Bonne Cove. The limestone beds have been deformed and contorted with dips up to 40° (southeast) recorded. Again, some of the more fractured areas have been reduced by weathering to a limestone gravel and this material is used locally on a very small scale for road aggregate (Plate 3).

Plate 3. *Small limestone pit north of Cooks Harbour. The stone is used locally for road aggregate.*

RESULTS AND RESERVE POTENTIAL

Table 2 (a and b) shows the results of the sampling program in the Cooks Harbour area. The results suggest that there are significant deposits of good quality stone available. The chemistry of the limestone is well within the specifications for a range of industrial applications, although the level of impurities (silica, iron, aluminum) in each of the two sampled areas is higher than that of the Burnt Island deposit.

At least 20 million tonnes of limestone could be quarried from the low-lying ridge north of the old Viking Highway (Figure 3), but potential reserves are much greater when one considers the areal extent of the Table Point Formation. The small peninsula north and west of Cooks Harbour, despite its relatively flat relief, could also provide a quarry site. This investigation concluded that the best stone underlies an area south of Square Cove and Bonne Cove. Table 2a depicts the results from a line of representative chip samples collected from that zone. The results indicate the presence of good-quality limestone although the recoverable amount is probably limited to less than 10 million tonnes. Cooks Harbour, a well-sheltered port, provides ocean access to the area's limestone resource.

Table 2. a) Chemical analyses for representative chip samples collected near Cooks Harbour; refer to Figure 3 for sample locations

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$
91	1.44	0.26	0.12	94.41	2.95
92	1.27	0.39	0.16	93.80	3.36
93	0.08	0.21	0.08	95.62	2.47
94	1.08	0.31	0.13	95.60	2.84
95	1.31	0.27	0.11	94.73	3.92
96	0.65	0.17	0.07	96.67	1.69
97	0.64	0.25	0.10	96.62	1.82
98	0.92	0.16	0.07	96.58	1.61
99	1.53	0.45	0.17	94.30	3.72
101	0.77	0.17	0.08	97.38	1.86
102	0.95	0.23	0.09	96.49	1.88
103	0.97	0.23	0.10	95.09	2.76
104	0.79	0.14	0.07	95.89	2.36
105	1.01	0.26	0.10	95.60	2.82
AVERAGE	1.02	0.25	0.10	95.63	2.58

b) Chemical analyses for chip samples collected across the Cooks Harbour (old Viking Highway) limestone; see Figure 3 for sample locations

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$
111	0.46	0.16	0.06	97.86	1.09
112	0.34	0.10	0.04	97.06	2.24
113	1.04	0.33	0.10	93.91	4.99
114	0.48	0.17	0.05	97.86	1.46
115	2.05	0.67	0.25	91.35	4.30
116	0.44	0.09	0.06	97.38	2.70
117	0.23	0.06	0.04	96.83	2.17
118	0.19	0.07	0.05	97.37	2.74
119	0.64	0.25	0.08	94.48	3.57
121	0.44	0.44	0.06	96.96	2.32
122	0.91	0.91	0.12	93.20	3.85
123	0.50	0.50	0.08	95.00	3.55
AVERAGE	0.64	0.31	0.09	95.77	2.91

CANADA BAY AREA

In addition to the high-purity white marble deposits currently under assessment by industry, the eastern side of the Northern Peninsula also host little-known but significant deposits of limestone. Knight (1987) observed that cement-grade stone underlies a large area to the north of Canada Bay (Figure 4). He further noted that the stone may also have potential as a building stone since it is thick bedded and contains attractive features such as fossils and depositional patterns.

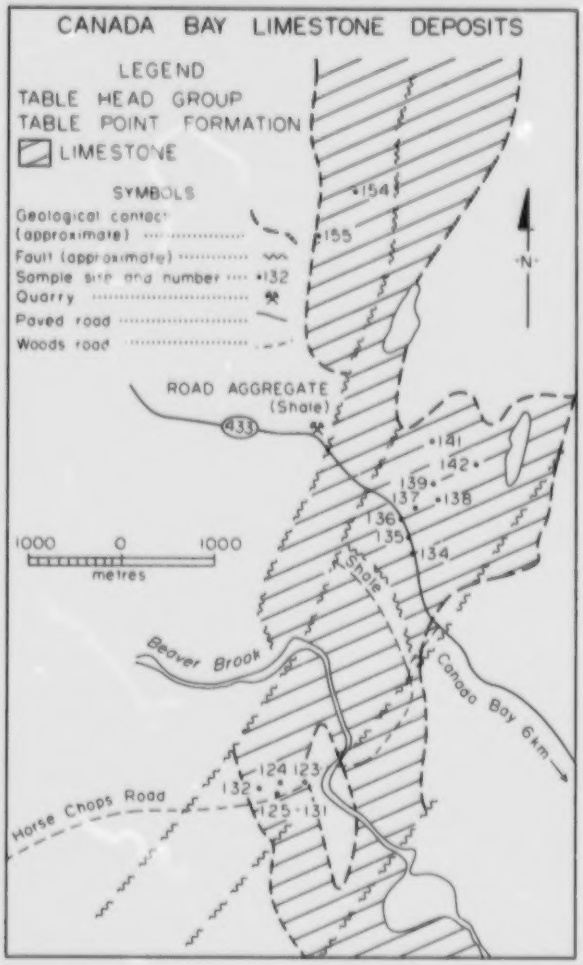
CANADA BAY LIMESTONE DEPOSITS
LEGEND
TABLE HEAD GROUP
TABLE POINT FORMATION
▨ LIMESTONE
SYMBOLS
Geological contact (approximate)
Fault (approximate)
Sample site and number •132
Quarry
Paved road
Woods road
N
ROAD AGGREGATE (Shale)
433
•154
155
•141
142•
139•
137
•138
136
135
134
1000 0 1000
metres
Shale
Beaver Brook
Canada Bay 6km
124 123
132•
125 131
Horse Chops Road

Figure 4. *Location of limestone deposits north of Canada Bay. (Geology after Knight, 1986b)*

During the present survey, a total of 28 samples were collected in order to provide essential chemical data on the limestone. Unlike the flat-lying, denuded limestone beds on the eastern side of the Great Northern Peninsula, here the limestone consists of poorly exposed formations underlying densely wooded ridges and valleys that have been extensively harvested for pulpwood.

The best exposures were noted about 5 km northwest of Beaver Arm and are accessible from the main highway via the Horse Chops access road (Figure 4). The thick-bedded limestone, which outcrops along a ridge, is light grey, has a fine-grained texture and looks fairly pure. The weathered surface is smooth and massive but the presence of a strongly developed cleavage precludes the use of this stone for building purposes. The light-grey stone overlies a 12 m section of dark-grey fossiliferous limestone, which contains thin seams of argillite near its top. At one point about midway through the section, the stone is weathered to a typical Table Head gravel. Black chert in minor amounts was noted in a highly fossiliferous, worm-burrowed outcrop of limestone a few metres west of the above section.

The northeast extension of the above belt of Table Head limestone was examined along Route 73 and along a network of woods roads immediately north of the highway. The topography in this area is very flat and in fact the road beds frequently consist of flat-lying beds of limestone. The dark-grey to black stone is weathered to a smooth surface and white veins of calcite are ubiquitous. The aerial extent of this stone is extensive and it would appear to have potential as a dimension stone, however, the lack of relief would make quarrying difficult.

SAMPLING RESULTS

The results of the sampling (Table 3) shows that the grade of the limestone in the sampled areas is remarkably similar to that found in the Cooks Harbour deposits (see Table 2a and b). The average grade of $CaCO_3$ (95.5 percent) is virtually the same as that for Cooks Harbour (95.7 percent), and the levels of impurities (silica, iron and aluminum) are also comparable. Also, the percentage of magnesium carbonate at 2.24 percent is only marginally lower than the 2.74 percent average for the Cooks Harbour limestone.

Table 3. Chemical analyses for representative chip samples from limestone formations north of Canada Bay; refer to Figure 4 for sample locations

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$
123	0.50	0.13	0.08	94.99	3.66
124	0.54	0.23	0.07	96.87	1.82
125	1.24	0.44	0.11	95.85	2.22
126	1.11	0.30	0.10	95.07	2.67
127	0.94	0.28	0.14	95.91	1.80
128	0.52	0.13	0.05	96.60	1.63
129	2.84	0.74	0.27	92.28	3.15
131	1.71	0.36	0.14	91.46	5.66
132	4.43	0.53	0.20	89.45	3.91
133	0.45	0.15	0.04	98.67	0.96
134	0.39	0.15	0.07	97.67	1.46
135	0.82	0.25	0.10	96.80	1.25
136	0.78	0.08	0.04	97.40	0.98
137	0.22	0.08	0.04	97.29	0.98
138	0.30	0.10	0.05	96.99	1.30
139	0.40	0.15	0.08	96.71	1.44
141	0.50	0.14	0.07	95.25	3.09
142	0.87	0.14	0.07	94.46	2.53
154	0.36	0.12	0.05	96.87	0.86
155	1.02	0.28	0.11	93.25	3.36
AVERAGE	1.00	0.23	0.09	95.49	2.24

These results indicate that significant deposits of good- to excellent-quality limestone can be delineated in the areas underlain by the Table Point Formation north of Canada Bay. However, the flatness of the topography makes it difficult to find good quarry sites.

SUMMARY

The Great Northern Peninsula is endowed with huge reserves of limestone suitable for most, if not all types of industrial uses, including chemical and metallurgical applications. The present study focused on deposits that are easily accessible by roads and located on, or very close to tidewater. Their suitability for quarry development in terms of topographic relief was also considered.

Chemical analyses of detailed representative chip samples confirmed field observations that Burnt Island, an unoccupied peninsula adjoining the fishing port of Raleigh, contains large reserves of extremely pure limestone. The deposit is also well suited for quarry development.

Sampling of two areas in the Cooks Harbour region showed that good-quality limestone is available, though the general flatness of the topography makes good quarry sites difficult to find and greatly reduces recoverable reserves. The same observations are valid for similar quality deposits north of Canada Bay on the eastern side of the Northern Peninsula. There, however, a thin although pervasive overburden cover presents an additional problem to potential developers. All of the limestone deposits examined during the present program require additional follow-up drilling assessments in order to provide more precise information on tonnages and grades.

ACKNOWLEDGMENTS

Barry Wheaton provided good help and companionship throughout the summer. Wayne Ryder was particularly helpful in getting us mobile when we became stuck in bureaucratic bogs. Dr. Henry Williams is thanked for the tour of the rocks and fossils of Table Point, one of the highlights of the season. Jamie Meyer is thanked for critically reviewing the manuscript.

REFERENCES

Bedford, J.P.
1957: Report on Coney Arm Limestone. British Newfoundland Exploration Company, Unpublished report, 5 pages. [12H/15 (291)]

Besaw, D.M.
1973: Limestone evaluation, Port au Port Peninsula. Newfoundland Department of Mines and Energy, Mineral Development Division, unpublished report, 49 pages. [12B (158)]

DeGrace, J.R.
1974: Limestone resources of Newfoundland and Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 74-2, 54 pages.

Hamer, C.A.
1986: Evaluation of SO_2 sorbent utilization in fluidized beds. CANMET, Mineral Sciences Laboratories, Energy Mines and Resources Canada, Ottawa, Report 86-9E, 75 pages.

Harris, I.
1962: Report on the 1962 brick shale–limestone survey party. Newfoundland Department of Mines, Agriculture, and Resources, Mineral Resources Division, unpublished report, 81 pages. [NFLD (216)]

Knight, I.
1986a: Geology of the Raleigh (2M/12) map area, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 86-26.

1986b: Geology of the Roddickton map area (12I/16), Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 86-24.

1987: Geology of the Roddickton map area (12I/16). *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 343-357.

Lee, B.W.
1956: Limestone investigation. Newfoundland Department of Mines and Resources, Unpublished report, 35 pages. [Nfld. (92)]

McKillop, J.H.
1961: Corner Brook limestone investigation. Newfoundland Department of Mines, Agriculture and Resources, Mineral Resources Division, unpublished report, 7 pages, 2 maps, and diamond-drill logs.

1963: Geology of the Corner Brook area, Newfoundland with emphasis on the carbonate deposits. Unpublished M.Sc. Thesis, Memorial University of Newfoundland, St. John's, 102 pages.

Power, T.
1985: Limestone specifications: limiting constraints on the market. *In* Industrial Minerals. October, 1985, pages 65-91.

Note: Geological Survey Branch file numbers are included in square brackets.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 327-334

PRELIMINARY EVALUATION OF RARE-METAL TARGETS IN INSULAR NEWFOUNDLAND

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ABSTRACT

Exploration for rare-metal mineralization in insular Newfoundland has been very sporadic, and has not yet evaluated all the potential targets. A preliminary field survey of 12 geological units on the Burin Peninsula, the Baie Verte Peninsula and in the Arnold's Cove to Traytown area was carried out to provide samples and field data for detailed laboratory analysis of these rare-metal exploration targets.

Units sampled include: the Kings Point complex, the Cape St. John Group and the spatially associated Seal Island Bight peralkaline granite, the Mic Mac Lake group, the Bull Arm Formation and the spatially associated Louil Hills peralkaline granite, the Mooring Cove Formation felsic volcanic rocks (English Harbour East area), the Cross Hills Plutonic Suite and the St. Lawrence peralkaline granite and its related volcanic−subvolcanic complexes (Grand Beach complex, Rocky Ridge complex, and Winterland porphyry). The Bull Arm Formation is divided into nine different segments due to the large areal extent of the formation; individual segments evaluated are Traytown, Port Blandford, Musgravetown, Plate Cove, Clarenville, Hodges Cove, Sunnyside, Masters Head and Doe Hills.

Radioactivity is the best field method to determine the rare-metal potential of an outcrop, particularly for volcanic and other fine-grained rocks. Most of the areas evaluated had radioactive values in the range 250 to 500 c.p.s. Areas that have outcrops with values above this range, and thus have medium to high rare-metal potential, are the Kings Point complex, the Louil Hills Intrusive Suite peralkaline granite, the Mooring Cove Formation, the Cross Hills Plutonic Suite peralkaline granite, the St. Lawrence peralkaline granite, the Grand Beach complex and the Musgravetown and Doe Hills segments of the Bull Arm Formation. All the samples will be analyzed for rare metals to better evaluate their potential and areas with favourable results will be further evaluated in follow-up work.

INTRODUCTION

Recent research on the rare-metal mineralization in the Strange Lake Zr−Y−Nb−Be−REE deposit (Miller, 1986) and in the Letitia Lake Nb−Be ± Y showings (Miller, 1987) has led to the development of an exploration model for rare-metal mineralization associated with felsic rocks (Miller, 1988). This model will be applied to felsic-rock settings in Labrador and insular Newfoundland, to evaluate the rare-metal potential and to encourage exploration activity for rare metals in the province; funding for this research will be provided by the Canada−Newfoundland Cooperation Agreement on Mineral Development 1990-1995. This past summer (1990), the first field season of the project, focussed on insular Newfoundland.

Rare-metal mineralization in Labrador occurs in high-level anorogenic intrusions and their near-vent extrusive equivalents (Miller, 1987), which are dominantly peralkaline and felsic in nature. Four geological settings−mineralization modes have been identified in Labrador (Miller, 1989):

1) pegmatite−aplite dykes and late-stage, roof-zone phases in high-level peralkaline granite plutons or associated satellite bodies that did not vent to the surface (e.g., Strange Lake peralkaline granite; Miller, 1989, 1990),

2) pegmatite and pegmatite−aplite dykes in the roof zone of vented peralkaline granites and disseminated mineralization in the near-vent extrusive equivalents or associated subvolcanic satellite bodies (e.g., Flowers River Igneous Suite, Shallow Lake peralkaline granite; Hill, 1981; Miller, 1989),

3) subvolcanic veins associated with peralkaline quartz syenites and disseminated mineralization in the associated peralkaline trachytes within the near-vent environment (e.g., Mann #1 and Two Tom Lake deposits; Miller, 1987), and,

4) disseminated mineralization within high-level, unvented(?), undersaturated peralkaline complexes (e.g., Red Wine Alkaline Intrusive complex; Curtis and Currie, 1981).

Most of these generalized geological settings have been identified in insular Newfoundland (Miller, 1989). Table 1

Table 1. Rare-metal exploration targets in insular Newfoundland

Setting	Area	Plutonic Phase	Volcanic Phase
Setting #2,3	Kings Point	Kings Point Complex (Per±)	Kings Point Complex (Per±)
Setting #1,2	La Scie	Seal Island Bight Peralkaline Granite ?	Cape St. John Group ? (Per?)
Setting #2,3	Mic Mac Lake	None identified	Mic Mac Lake Group (Per?)
Setting #1,2	Clarenville	Louil Hills Peralkaline Granite ?	Bull Arm Formation ? (Per?)
Setting #1,2	English Harbour	Cross Hills Peralkaline Granite ?	Mooring Cove Formation ? (Per?)
Setting #2,3	Burin Peninsula	St. Lawrence Peralkaline Granite	Rocky Ridge Complex (Per)
Setting #2,3	Burin Peninsula	Winterland Porphyry (Per?)	None identified
Setting #2,3	Burin Peninsula	Grand Beach Complex (Per?)	Grand Beach Complex (Per?)

Per?	Peralkaline nature not well established, may have peralkaline trace-element characteristics but does not have peralkaline major-element characteristics.
Per±	Definitely peralkaline at some outcrops; not peralkaline or questionably peralkaline in others
?	Age and petrological relationships between plutonic and volcanic rocks is unknown.

lists the areas and geological units chosen for this study and the rare-metal setting expected in these areas. Each of these areas is being evaluated initially by reconnaissance mapping and sampling programs. All outcrops visited are assessed for rare-metal mineralization; selected outcrops are measured for radioactivity (total counts using an EDA GRS-500 Spectrometer) and sampled for geochemical and/or thin-section analyses. Samples collected will be petrographically studied and geochemically analyzed to help determine the rock type and degree of peralkalinity (a key factor in rare-metal environments), and to determine the representative rare-metal values of the outcrop.

RARE-METAL TARGETS IN NEWFOUNDLAND

The best regional rare-metal targets are felsic volcanic rocks and related intrusive rocks from complexes that are peralkaline, have peralkaline affinities (e.g., high values of Zr, Nb, U, F, REE) or are associated with peralkaline rocks. Units targeted for sampling this summer (Figures 1 and 2) include: the Kings Point complex, the Cape St. John Group and the spatially associated Seal Island Bight peralkaline granite, the Mic Mac Lake group, the Bull Arm Formation (Musgravetown Group) and the spatially associated Louil Hills Intrusive Suite peralkaline granite, the Mooring Cove Formation (Long Harbour Group) felsic volcanic rocks (English Harbour East area), the Cross Hills Plutonic Suite and the St. Lawrence peralkaline granite and its related volcanic–subvolcanic complexes (Figure 3; Grand Beach complex, Rocky Ridge complex, and Winterland porphyry). All target suites were sampled and reconnaissance mapped. Other suites, including the Hare Hill peralkaline granite and Topsails Intrusive Suite (including felsic volcanic rocks of the Sheffield Lake area), will be sampled during 1991.

The sampled areas can be characterized as follows:

1. Kings Point complex (Mercer *et al.*, 1985; Kontak and Strong, 1986)–A felsic subvolcanic–volcanic complex, which consists of peralkaline and non-peralkaline trace-element-enriched granites, porphyries, porphyritic syenite, ash flows, lava flows and breccias (contains the vented granite–syenite and volcanic equivalents of Setting 2 and 3, Table 1; mineralization may occur as veins or pegmatites).

2. Seal Island Bight peralkaline granite (Whalen *et al.*, 1986; DeGrace *et al.*, 1976)–This consists of a riebeckite-bearing peralkaline granite (if the nearby spatially associated Cape St. John Group felsic volcanic rocks are peralkaline or have peralkaline affinity then Setting 2 is applicable, otherwise this is an unvented granite of Setting 1).

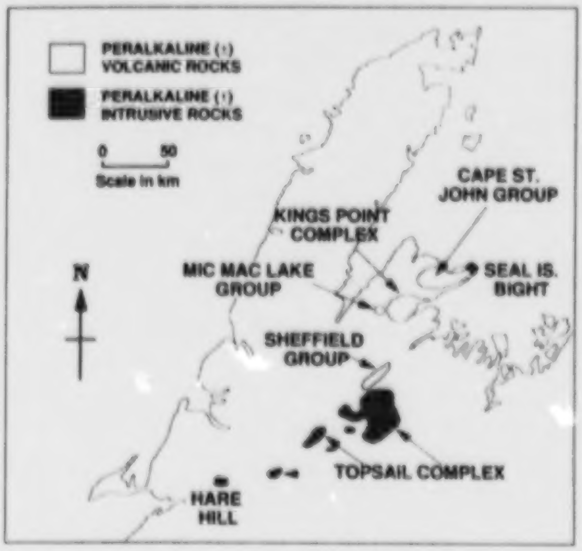

PERALKALINE (±) VOLCANIC ROCKS
PERALKALINE (±) INTRUSIVE ROCKS
0 50
Scale in km
N
CAPE ST. JOHN GROUP
KINGS POINT COMPLEX
MIC MAC LAKE GROUP
SEAL IS. BIGHT
SHEFFIELD GROUP
TOPSAIL COMPLEX
HARE HILL

Figure 1. *Rare-metal targets in northwestern Newfoundland; peralkaline and peralkaline-related volcanic and high-level plutonic rocks.*

3. Cape St. John Group (DeGrace *et al.*, 1976)—Dominated by ash-flow tuffs and aphanitic to slightly porphyritic rhyolitic flows and pyroclastics; also includes Cape Brulé Porphyry; (this group could contain mineralized volcanic rocks or veins of Setting 2).

4. Mic Mac Lake group (DeGrace *et al.*, 1976; Hibbard, 1983)—Volcanic—sedimentary sequence consisting of mafic flows, conglomerate, felsic ignimbrite and porphyry, and trachytic flows (may contain mineralized flows or veins of Settings 2 or 3).

5. Bull Arm Formation (King, 1988; Colman-Sadd *et al.*, 1990)—Consists of mafic flows, felsic to intermediate, massive to feldspar porphyritic flows and ash-flow tuffs (mineralization may occur as veins or disseminated in volcanic rocks of Setting 2).

6. Louil Hills peralkaline granite (O'Brien, 1987; O'Brien *et al.*, 1988)—Ranges from riebeckite-bearing fine- to medium-grained peralkaline granite (either Setting 1 or 2 depending on the relationship between the peralkaline granite and the nearby Bull Arm Formation rhyolitic volcanic rocks).

7. Mooring Cove Formation, English Harbour East area (O'Brien *et al.*, 1984)—Consists of rhyolitic massive to banded flows, flow breccia and ash-flow tuffs (occurs in Setting 1 or 2 depending on the age—petrological relationship between these volcanic rocks and the Cross Hills Plutonic Suite peralkaline granite).

8. Cross Hills Plutonic Suite peralkaline granite (Saunders and Tuach, 1989)—Peralkaline phases are aplitic, fine- or medium-grained granite (mineralization occurs in Setting 1 or 2 depending on the petrological relationship with the spatially associated Mooring Cove Formation).

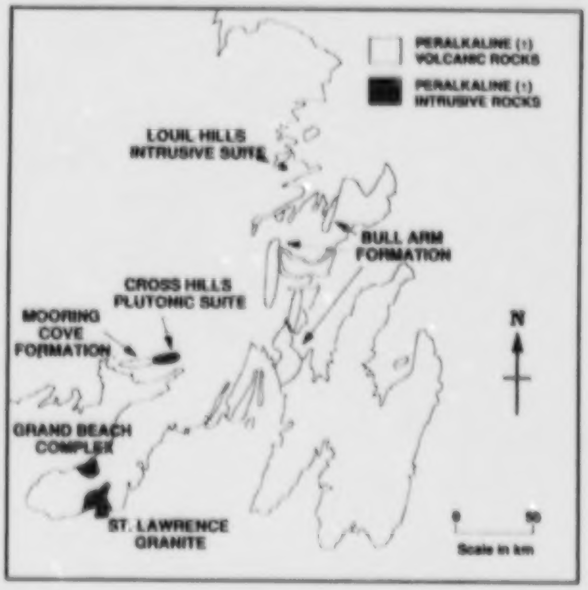

PERALKALINE (±) VOLCANIC ROCKS
PERALKALINE (±) INTRUSIVE ROCKS
LOUIL HILLS INTRUSIVE SUITE
BULL ARM FORMATION
CROSS HILLS PLUTONIC SUITE
MOORING COVE FORMATION
N
GRAND BEACH COMPLEX
ST. LAWRENCE GRANITE
0 50
Scale in km

Figure 2. *Rare-metal targets in southeastern Newfoundland; peralkaline and peralkaline-related volcanic and high-level plutonic rocks.*

9. St. Lawrence peralkaline granite (Strong *et al.*, 1978; O'Brien *et al.*, 1977)—Consists of porphyritic and medium-grained granite, quartz—feldspar porphyry, and amphibole syenite (known mineralization in fluorite-rich veins of Setting 2).

10. Grand Beach complex (Strong *et al.*, 1978; O'Brien *et al.*, 1977)—Dominated by quartz—feldspar porphyry and ash-flow tuffs associated with minor rhyolitic flows (may be related to the St. Lawrence peralkaline granite and thus be in Setting 2).

11. Rocky Ridge complex (Strong *et al.*, 1978)—Observed to contain quartz—feldspar porphyry, amphibole—quartz syenite and felsic ash flows (occurs in Setting 2 or 3).

12. Winterland porphyry (Strong *et al.*, 1978)—Characterized by very poor outcrop; observed outcrops are quartz—feldspar porphyry and porphyritic amphibole syenite (probably occurs in Setting 3).

PRELIMINARY EVALUATION OF TARGETS

The modes of occurrence of rare-metal mineralization makes it difficult to visually identify it in the field. Rare-metal-bearing pegmatitic lenses, veins and dykes, as found in Settings 1, 2 and 3, are usually the easiest to identify if the rare-metal minerals are coarse grained. However, aplitic, fine-grained and disseminated mineralization, particularly in the volcanic environments of Settings 2 and 3, is very difficult

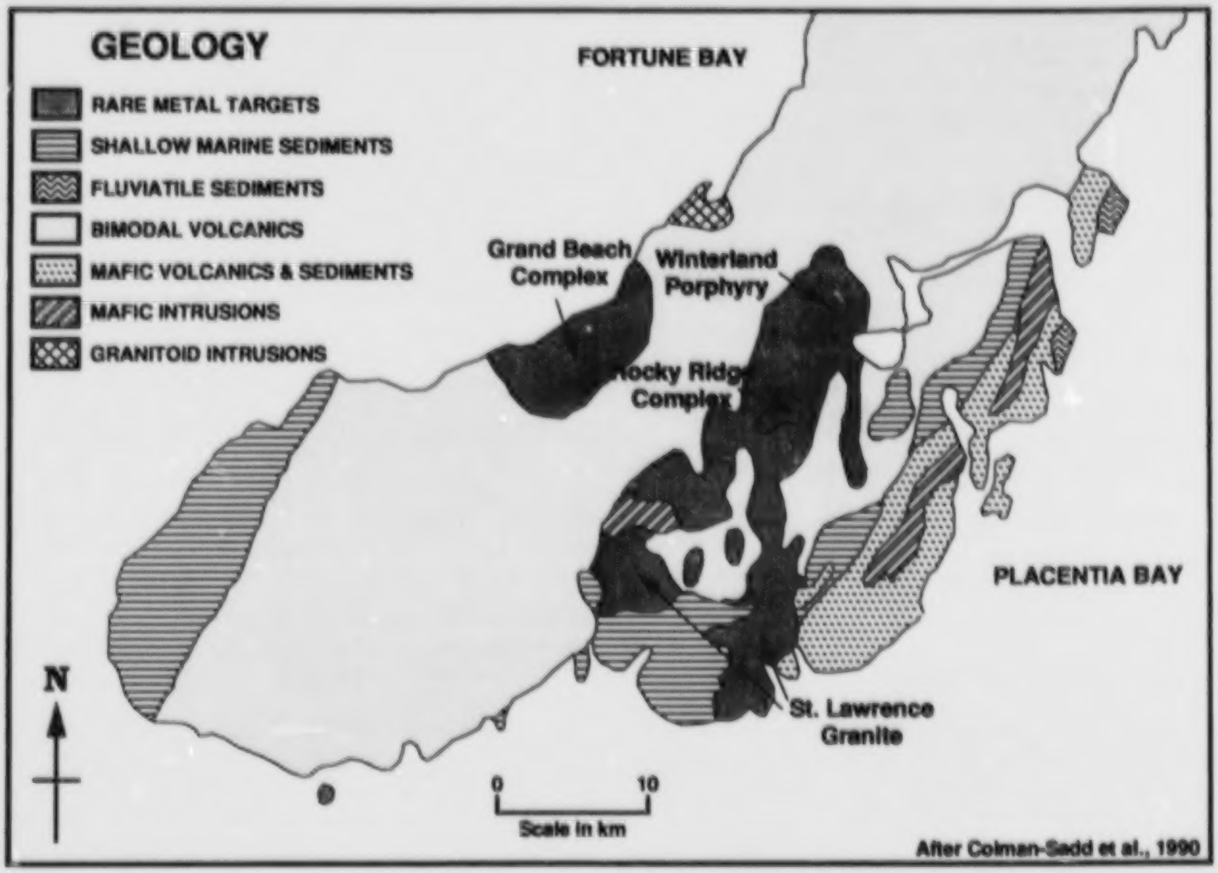

GEOLOGY
RARE METAL TARGETS
SHALLOW MARINE SEDIMENTS
FLUVIATILE SEDIMENTS
BIMODAL VOLCANICS
MAFIC VOLCANICS & SEDIMENTS
MAFIC INTRUSIONS
GRANITOID INTRUSIONS
FORTUNE BAY
Grand Beach Complex
Winterland Porphyry
Rocky Ridge Complex
PLACENTIA BAY
St. Lawrence Granite
N
0
10
Scale in km
After Colman-Sadd et al., 1990

Figure 3. *General geology of the southern portion of the Burin Peninsula; location of the Grand Beach complex, Winterland porphyry, Rocky Ridge complex and St. Lawrence Granite (after Colman-Sadd* et al., *1990).*

to verify due to the fine grainsize. Thus, rare-metal potential cannot be very accurately evaluated in many areas before chemical analyses are available.

A tentative positive correlation between rare-metal content and radioactivity (total counts) in samples studied from both the Letitia Lake showings and the Strange Lake deposit, indicates that radioactivity can be used to determine rare-metal potential. As rare-metal analyses are presently lacking for the samples collected to date, radioactivity, degree of peralkalinity and similarity of environment with known deposits and showings, will be used to make a preliminary evaluation of the rare-metal targets.

These criteria have been applied to the samples collected from the 1990 target areas to give a qualitative idea of the amount of rare metals present; low potential is of no economic interest, medium potential needs further evaluation and high potential suggests rare-metal values of economic interest. The following is a preliminary evaluation of the target areas.

I. Kings Point complex—The quartz—feldspar porphyry, quartz syenite and porphyritic granite of this complex (Figure 4) commonly have total count (TC-1) radiometric values of between 225 and 280 c.p.s., whereas the porphyritic syenite and the ash-flow tuff outcrops usually give values of between 300 and 400 c.p.s. Anomalous values of between 420 and 800 c.p.s. are found in outcrops of phenocryst-poor porphyry, amphibole-bearing porphyry and flow-banded breccias, in certain areas of the complex. The best indication of mineralization was one highly radioactive pegmatite—aplite vein (<10 cm thick), which had values between 2000 and 3500 c.p.s. Pegmatite—aplite veins in the Strange Lake deposit host rare-metal mineralization and commonly have radioactivity measurements above 1000 c.p.s. These observations suggest that parts of the Kings Point complex have high rare-metal potential.

II. Cape St. John Group—The volcanic rocks of this group generally exhibit low radioactivity (200 to 310 c.p.s.) and are probably low in rare metals. Some isolated outcrops of aphanitic volcanic rocks have radioactivity up to 550 c.p.s.; chemical data is needed to better evaluate these outcrops. The Cape Brulé Porphyry is characterized by generally higher radioactivity, 270 to 430 c.p.s., than the surrounding volcanic rocks. Radioactivity and field observations indicate that the

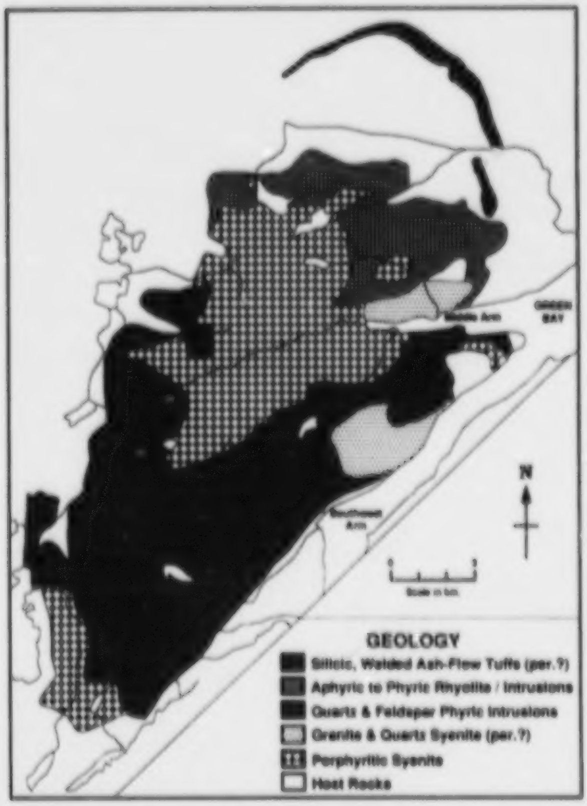

GREEN BAY
Middle Arm
Southwest Arm
N
Scale in km
GEOLOGY
■ Silicic, Welded Ash-Flow Tuffs (per.?)
▨ Aphyric to Phyric Rhyolite / Intrusions
■ Quartz & Feldspar Phyric Intrusions
▨ Granite & Quartz Syenite (per.?)
▨ Porphyritic Syenite
☐ Host Rocks

Figure 4. *General geology of the Kings Point complex (after Mercer* et al., *1985; Kontak and Strong, 1986).*

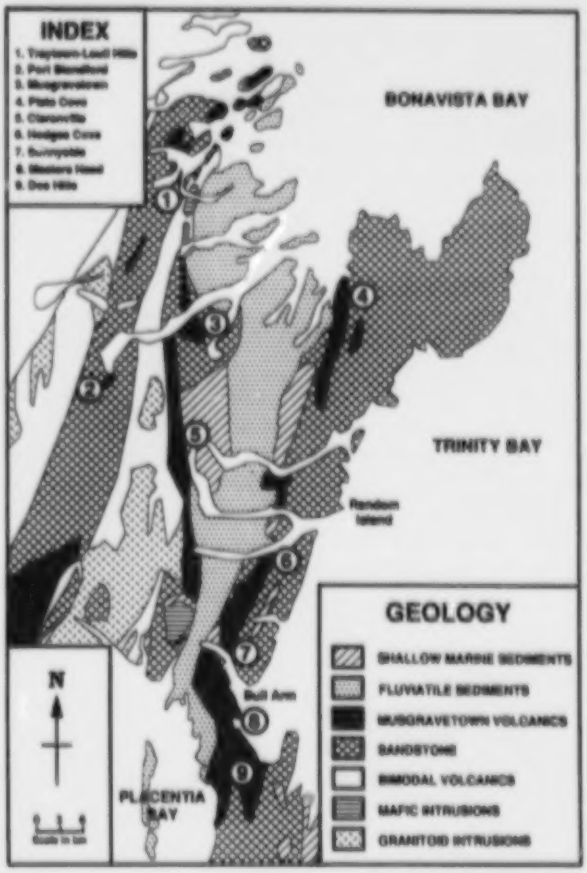
Cape St. John Group is not a good candidate for rare-metal mineralization. Isolated volcanic units and parts of the porphyry may be of interest.

III. Seal Island Bight peralkaline granite–Even though this is a peralkaline granite, the radioactivity is relatively low (200 to 300 c.p.s.), which suggests low rare-metal content; pegmatite–aplite veins were not observed in outcrop.

IV. Mic Mac Lake group–Low to medium radioactivity, from 200 to 400 c.p.s., indicate a low rare-metal potential. This group was not extensively sampled.

V. Bull Arm Formation–The Bull Arm Formation target area was broken down into several segments due to the large areal extent of the formation (Figure 5). These segments are located in the Traytown, Port Blandford, Musgravetown, Plate Cove, Clarenville, Hodges Cove, Sunnyside, Masters Head and the Doe Hills areas. Segments containing outcrops of medium to high relative radioactivity and thus, medium to high rare-metal potential include: Musgravetown and Doe Hills.

1) Traytown–Minor units of felsic to intermediate tuffs and flows in this area have radioactivity values of between 140 and 260 c.p.s. These volcanic rocks appear to have very low rare-metal potential.


INDEX
1. Traytown
2. Port Blandford
3. Musgravetown
4. Plate Cove
5. Clarenville
6. Hodges Cove
7. Sunnyside
8. Masters Head
9. Doe Hills
BONAVISTA BAY
TRINITY BAY
Random Island
Bull Arm
PLACENTIA BAY
N
Scale in km
①
②
③
④
⑤
⑥
⑦
⑧
⑨
GEOLOGY
▨ SHALLOW MARINE SEDIMENTS
▨ FLUVIATILE SEDIMENTS
■ MUSGRAVETOWN VOLCANICS
▨ SANDSTONE
☐ BIMODAL VOLCANICS
▨ MAFIC INTRUSIONS
▨ GRANITOID INTRUSIONS

After Colman-Sadd et al., 1990

Figure 5. *General geology of the Traytown to Doe Hills area, eastern Newfoundland; indicates the locations of the sampled areas in the Bull Arm Formation of the Musgravetown Group (after Colman-Sadd* et al., *1990).*

2) Port Blandford–Samples, collected from felsic flows and tuffs, in this area give low radioactivity values in the range 220 to 250 c.p.s. Rare-metal potential is very low.

3) Musgravetown–Felsic flows range from 300 to 720 c.p.s. in this area. Several units have values in the upper part of this range and thus have medium to high potential for rare metals.

4) Plate Cove–Felsic flows and porphyries in the Plate Cove area exhibit a range of radioactivity values of between 270 and 410 c.p.s. Samples with values in the upper part of this range may have some rare-metal potential, but this area generally has low potential.

5) Clarenville–Feldspar porphyritic flows in this area range from 210 to 420 c.p.s. Most of these flows have very low rare-metal potential but those with higher radioactivity values may have some potential and must await chemical analysis.

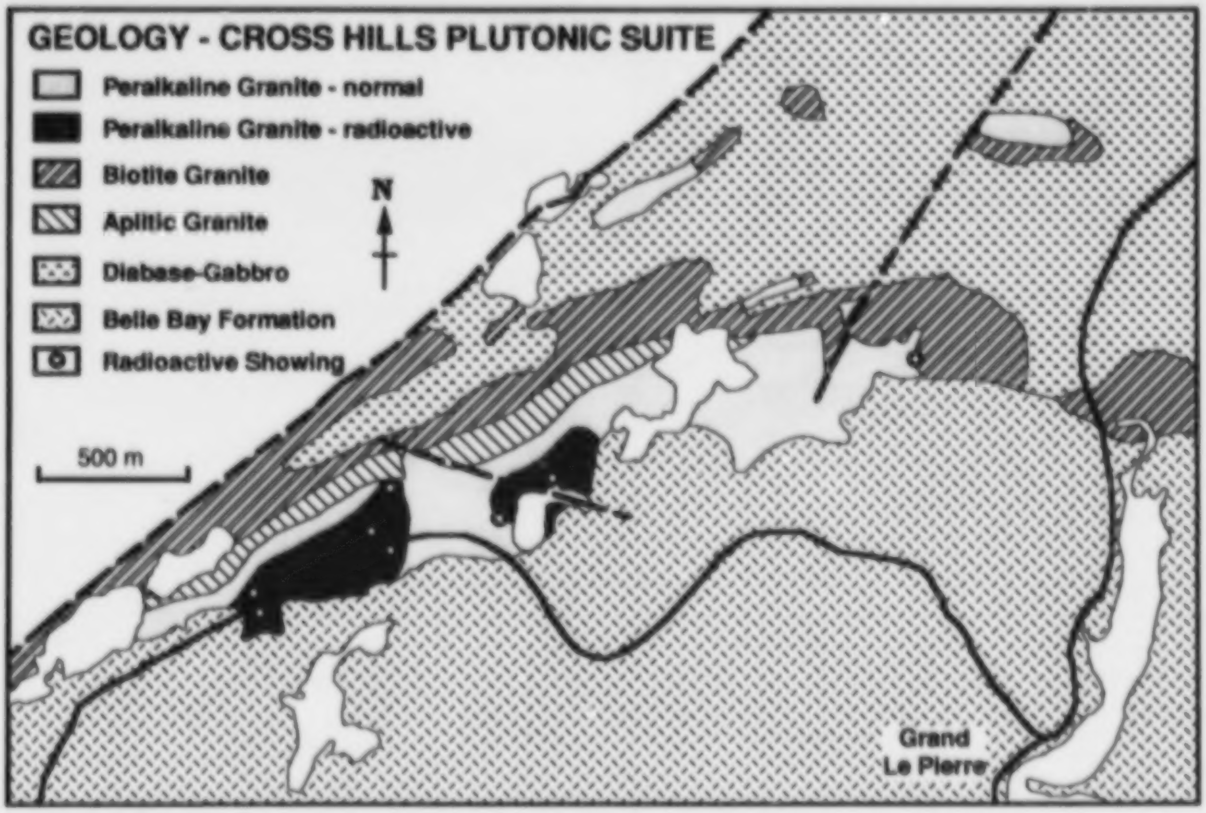


Figure 6. *Geology of the Cross Hills Plutonic Suite; location of radioactive showings and the radioactive peralkaline granite (after Saunders and Tuach, 1989).*

6) Hodges Cove—The few samples of felsic to intermediate tuffs or flows collected from this area have very low radioactivity (250 to 270 c.p.s.) and thus, low rare-metal potential.

7) Sunnyside—Felsic rocks in the Sunnyside area range from 185 to 480 c.p.s. Ash-flow tuffs, porphyries and flows have examples throughout this range. Values in the upper portion of the range suggest local units having medium rare-metal potential although most other units have low potential.

8) Masters Head—The felsic porphyries and ash-flow tuffs in this area range from 200 to 380 c.p.s., and thus have a low potential.

9) Doe Hills—Felsic ash-flow tuffs, porphyries and flows in this area form two groups based on radioactivity. One group has a range of 210 to 360 c.p.s., with most outcrops exhibiting values above 300 c.p.s.; the second group has a range of 480 to 540 c.p.s. The outcrops from the second group have a medium rare-metal potential.

VI. Louil Hills peralkaline granite—This peralkaline granite, as observed in samples from outside of the Terra Nova National Park, appears to have a high potential for rare-metal mineralization as indicated by zones of high spot radioactivity (750 to 900 c.p.s.). It also has a higher general radioactivity than many of the other suites studied (400 to 500 c.p.s.), including the Seal Island Bight peralkaline granite, which is similar in composition.

VII. Mooring Cove Formation—Felsic flows and tuffs exhibit mainly low to medium radioactivity (240 to 360 c.p.s.). Several samples with high radioactivity (600 and 700 c.p.s.) suggest that there are some units of this formation that have medium to high rare-metal potential.

VIII. Cross Hills complex—Two separate bodies of Cross Hills peralkaline granite, the Bark Pond and the northeast occurrences, were sampled and measured for radioactivity. This fine-grained to medium-grained granite can be divided into two groups, a medium radioactivity group (370 to 440 c.p.s.), found at both occurrences, and a high radioactivity group (475 to 1020 c.p.s.), found only at the Bark Pond occurrence (Figure 6). A large number of small radioactive (880 to 1400 c.p.s.) pegmatite—aplite veins (< 15 cm wide) and pods occur within the zone of highly radioactive medium-grained granite. These high values of radioactivity, along with some analyses from these rocks (Saunders and Tuach, 1989), indicate that the Cross Hills peralkaline granite has a high potential for rare-metal mineralization. This setting for rare-metal mineralization is very similar to that at the Strange Lake deposit and thus, should be thoroughly evaluated.

IX. St. Lawrence peralkaline granite—The two major phases of this granitic complex exhibit fairly similar radioactive values. The porphyritic granite phase has values in the range of 370 to 570 c.p.s. and an average of 460 c.p.s. (15 samples) whereas the medium-grained granite phase has a range of 370 to 610 c.p.s., with two observed highs of 720 and 860 c.p.s., and an average value of 510 c.p.s. (23 samples); other minor phases have similar values. These values indicate that there are large segments of this granite, which have medium to high potential for rare-metal mineralization; the two high values may indicate areas for detailed follow-up work. Previous analyses for Y in fluorite from fluorite veins (Strong *et al.*, 1984) indicate that these veins have good potential for Y mineralization, yet radioactivity values in the range 250 to 380 c.p.s. suggest the opposite. A correlation between radioactivity and rare-metal contents in fluorite veins may not exist as it does for granitic bodies and volcanic rocks. The overall radioactivity of this granite is very high and suggests that there is a medium to high potential for rare-metal mineralization.

X. Rocky Ridge complex—The rocks of this complex have low to medium radioactivity (range of 230 to 470 c.p.s.). There appears to be very low potential in this area.

XI. Winterland porphyry—Very rare outcrop has limited the ability to evaluate the rocks of this complex and to establish its bedrock extent. One sample of quartz—feldspar porphyry, several of amphibole-bearing quartz syenite and several of feldspar porphyry were taken from outcrops thought to be in the outcrop area of this complex. Radioactivity measurements range from 230 to 370 c.p.s., with most being below 260 c.p.s. These results indicate that the rare-metal potential is low. The difference in overall radioactivity of the Winterland porphyry rocks verses the St. Lawrence Granite suggests that these rocks are not as closely related as previously thought (Strong *et al.*, 1978).

XII. Grand Beach complex—Much of this complex is characterized by quartz—feldspar porphyry and quartz—feldspar porphyritic ash-flow tuffs with minor felsic flows, debris flows and tuffs. The quartz—feldspar porphyry has a range of radioactivity values of 280 to 400 c.p.s. with an average of 360 c.p.s. (10 samples), whereas the ash-flow tuffs have a range of 330 to 650 c.p.s. with an average of 430 c.p.s. (12 samples). The minor units have values in the range of 260 to 680 c.p.s. The most interesting values, above 500 c.p.s., occur in the ash-flow tuffs (525, 545 and 650 c.p.s.) and in one outcrop area of felsic flows (680 c.p.s.) observed in the complex. The small areas within the complex, which exhibit medium radioactivity, appear to have medium-high rare-metal potential. The Grand Beach complex is generally much lower in radioactivity than the St. Lawrence Granite and thus, may not be as closely related as previously thought (Strong *et al.*, 1978).

CONCLUSIONS

At present, only field observations and radioactivity measurements are available for the samples collected. These data, in particular the radioactivity values, can only be used to make a preliminary evaluation of rare-metal potential.

Most areas sampled have radioactive background values in the 250 to 500 c.p.s. range. Areas that have outcrops with values above this range, and thus have medium to high rare-metal potential, are: Kings Point complex, Louil Hills peralkaline granite, Mooring Cove Formation, Cross Hills peralkaline granite, St. Lawrence peralkaline granite, Grand Beach complex and the Musgravetown and Doe Hills areas of the Bull Arm Formation. One pegmatite—aplite vein in the Kings Point complex and several pegmatite—aplite or pegmatite veins in the Cross Hills peralkaline granite have radioactivity measurements above 1000 c.p.s.; these areas are of particular interest because the mode and radioactive values of the mineralization is similar to that observed in the Strange Lake peralkaline granite.

Geochemical and other data are required to further evaluate these rare-metal targets. Laboratory studies are ongoing. Reconnaissance sampling of other targets in insular Newfoundland, including the Hare Hill peralkaline granite and Topsails Intrusive Suite (including felsic volcanics of the Sheffield Lake area), and some within Labrador will be carried out during the 1991 field season. A detailed sampling and mapping program will also be carried out in the Flowers River Igneous Suite felsic volcanic rocks in 1991. The more encouraging areas, subsequently identified in geochemical and other studies, will be the subject of a follow-up program in the following field season.

ACKNOWLEDGMENTS

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REFERENCES

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. (Compilers)
1990: Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-01.

Curtis, L.W. and Currie, K.L.
1981: Geology and petrology of the Red Wine Alkaline Complex, central Labrador. Geological Survey of Canada, Bulletin 294.

DeGrace, J.R., Kean, B.F., Hsu, E. and Green, T.
1976: Geology of the Nippers Harbour map area (2E/13), Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 76-3, 73 pages.

Hibbard, J.
1983: Geology of the Baie Verte Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Memoir 2, 276 pages.

Hill, J.D.
1981: Geology of the Flowers River area, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 81-6, 40 pages.

King, A.F.
1988: Geology of the Avalon Peninsula, Newfoundland (parts of 1K, 1L, 1M, 1N, and 2C). Newfoundland Department of Mines, Mineral Development Division, Map 88-01.

Kontak, D.J. and Strong, D.F.
1986: The volcano-plutonic King's Point complex, Newfoundland. *In* Current Research, Part A. Geological Survey of Canada, Paper 86-1A, pages 465-470.

Mercer, B., Strong, D.F., Wilton, D.H.C. and Gibbons, D.
1985: The King's Point Complex, western Newfoundland. *In* Current Research, Part A. Geological Survey of Canada, Paper 85-1A, pages 737-741.

Miller, R. R.
1986: Geology of the Strange Lake Alkalic Complex and the associated Zr–Y–Nb–Be–REE mineralization. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 11-19.

1987: The relationship between Mann-type Nb-Be mineralization and felsic peralkaline intrusives, Letitia Lake Project, Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 83-91.

1988: Yttrium (Y) and other rare metals (Be, Nb, REE, Ta, Zr) in Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 229-245.

1989: Rare-metal targets in insular Newfoundland. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 171-179.

1990: The Strange Lake pegmatite–aplite-hosted rare-metal deposit, Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 171-182.

O'Brien, S.J.
1987: Geology of the Eastport (west half) map area, Bonavista Bay, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 257-270.

O'Brien, S.J., Nunn, G.A.G., Dickson, W.L. and Tuach, J.
1984: Geology of the Terrenceville (1M/10) and Gisborne Lake (1M/15) map areas, southeast Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-4, 54 pages.

O'Brien, S.J., Strong, P.G. and Evans, J.L.
1977: The geology of the Grand Bank (1M/4) and Lamaline (1L/13) map areas, Burin Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-7, 16 pages.

O'Brien, S.J., O'Neil, P.P., King, A.F. and Blackwood, R.F.
1988: Eastern margins of the Newfoundland Appalachians–A cross-section of the Avalon and Gander Zones. Geological Association of Canada–Mineralogical Association of Canada Field Trip Guidebook B4, pages 80-81.

Saunders, C.M. and Tuach, J.
1989: Zr-Nb-Y-REE mineralization in the Cross Hills Plutonic Suite. *In* Current Research. Newfoundland Department of Mines, Geological Survey of Newfoundland, Report 89-1, pages 181-192.

Strong, D.F., Fryer, B.J. and Kerrich, R.
1984: Genesis of the St. Lawrence fluorspar deposits as indicated by fluid inclusion, rare earth element, and isotopic data. Economic Geology, Volume 79, pages 1142-1158.

Strong, D.F., O'Brien, S.J., Taylor, S.W., Strong, P.G. and Wilton, D.H.
1978: Geology of the Marystown (1M/3) and St. Lawrence (1L/14) map areas, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-8, 81 pages.

Whalen, J.B., Currie, K.L. and Chappell, B.W.
1986: A-Type Granites: Descriptive and geochemical data. Geological Survey of Canada, Open File 1411, 33 pages.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 335-347

MINERALIZATION IN WESTERN WHITE BAY

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Mineral Deposits Section

ABSTRACT

The western White Bay area has a complex metallogeny, characterized by three broad styles of mineralization: i) structurally controlled mesothermal gold mineralization, ii) stratabound carbonate-hosted galena mineralization and iii) granite-hosted fluorite and molybdenite mineralization. The gold mineralization occurs in a variety of units of different ages and rock types. The mineralization and related alteration appear to be concentrated along fault and shear zones and may crosscut lithological contacts, e.g., at Rattling Brook. The alteration assemblages and variety of host rocks, along with the presence of CO_2-rich fluid inclusions in associated quartz gangue, suggest that the mineralization formed at considerable depths and is mesothermal rather than epithermal as has been previously suggested. It is possible that most of the gold occurrences in the western White Bay area formed as a result of large-scale, deep-seated hydrothermal circulation during late Silurian or younger times. The carbonate-hosted galena mineralization is found in brecciated dolostone within the Lower Volcanic formation. This mineralization is not enriched in gold and may have formed from fluids emanating from the Carboniferous Deer Lake Basin to the south. The granite-hosted fluorite and molybdenite mineralization is minor and is found within the Gull Lake intrusive suite and related aplitic dykes. It is likely related to late-stage magmatic processes and is probably not related to the gold mineralization in the area.

INTRODUCTION

This report is a partial compilation of metallic mineral occurrences in the western White Bay area. These data have been compiled as part of a larger forthcoming report (Tuach and Saunders, *in preparation*) produced as the result of a five-year metallogenic study of the area.

The western White Bay area has had a long but sporadic history of mineral exploration beginning with the discovery of the West Corner Brook gold showing in 1898, and the working of the Browning gold mine in 1903. In the mid 1930's the Simms Ridge and Freemans prospects were discovered and trenched and the Browning Mine was re-examined. Other than a reconnaissance survey by Newmont in the 1960's, little work was done in the area until the late 1970's, when Noranda Exploration Company Limited discovered the Turners Ridge Prospect. However, during the 1980's, exploration activity has increased substantially, sparked by the discovery of the Rattling Brook gold deposit and the release of much ground that had been tied up under the old concession system.

The Department of Mines and Energy began a metallogenic study of the area in 1985. This work has been documented in several papers and field-trip guides including those by Tuach (1986, 1987a, b), Tuach and French (1986), Tuach *et al.* (1988), Saunders and Tuach (1988), and Tuach and Saunders (1990). The present paper presents a metallogenic synthesis of the western White Bay area, drawing heavily on these reports and on the data presented in numerous mineral exploration assessment reports on open file with the Newfoundland Department of Mines and Energy. Emphasis has been placed on gold-bearing occurrences and many small base-metal-only indications have not been described. The work has shown that the western White Bay area is host to at least three broad styles of mineralization, namely structurally controlled gold mineralization, stratabound carbonate-hosted lead mineralization, and minor granite-hosted fluorite and molybdenite mineralization. This paper describes significant examples of the occurrences and presents some interim conclusions concerning their various types of genesis.

GENERAL GEOLOGY

The regional geology of the White Bay area has been described by Smyth and Schillereff (1982) and Tuach (1987a, b). The area is bisected by the Doucers Valley fault complex, a major structural lineament that juxtaposes middle to late Proterozoic granitic and gneissic basement and Eocambrian to Cambrian platformal sediments to the west, with Paleozoic oceanic and continental volcanic and sedimentary rocks to the east (Figures 1 and 2). The fault complex has a long history of brittle and ductile movement dating from as early as Ordovician to Late Carboniferous or younger (Lock, 1969, 1972; Hyde, 1979; Tuach, 1987a).

The oldest rocks in the area are Precambrian quartzofeldspathic gneisses of the basement Long Range Inlier, which outcrops west of the Doucers Valley fault complex. These are intruded by late Proterozoic megacrystic to equigranular, granodioritic to granitic bodies, including the Apsy and Main River plutons. The gneisses and intrusive rocks are unconformably overlain by platformal clastic rocks

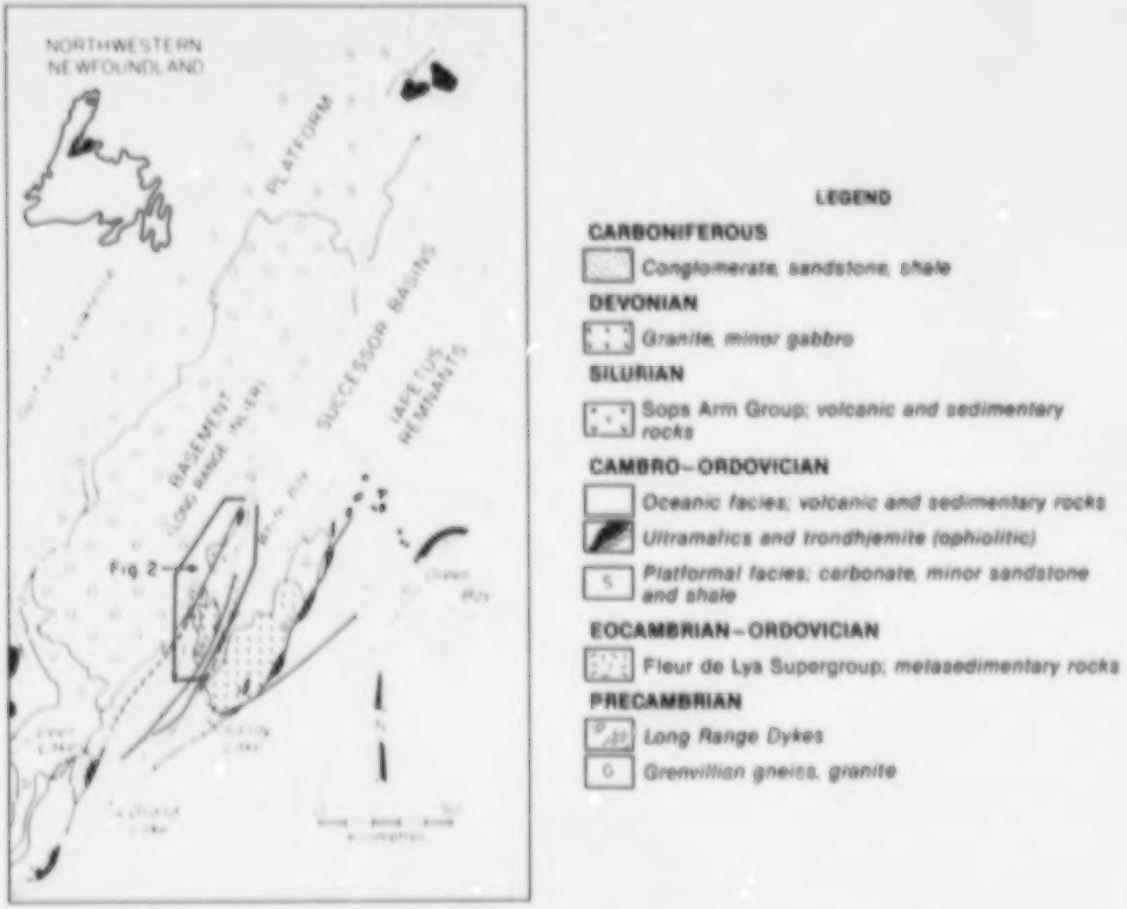

NORTHWESTERN
NEWFOUNDLAND
PLATFORM
SUCCESSOR BASINS
IAPETUS
REMNANTS
BASEMENT
(LONG RANGE INLIER)
Fig 2
White
Bay
LEGEND
CARBONIFEROUS
Conglomerate, sandstone, shale
DEVONIAN
Granite, minor gabbro
SILURIAN
Sops Arm Group; volcanic and sedimentary rocks
CAMBRO-ORDOVICIAN
Oceanic facies; volcanic and sedimentary rocks
Ultramafics and trondhjemite (ophiolitic)
Platformal facies; carbonate, minor sandstone and shale
EOCAMBRIAN-ORDOVICIAN
Fleur de Lys Supergroup; metasedimentary rocks
PRECAMBRIAN
Long Range Dykes
Grenvillian gneiss, granite

Figure 1. *General geology and tectonic elements of northwestern Newfoundland (from Tuach, 1987a). DVFC–Doucers Valley fault complex; BVL–Baie Verte Lineament; BRF–Birchy Ridge fault; HF–Hampden fault.*

and carbonates of the Eocambrian to Cambrian Coney Arm Group.

The Paleozoic rocks to the east of the Doucers Valley fault complex include Cambro-Ordovician ophiolitic, volcanic and volcaniclastic sequences of the Southern White Bay Allochthon (Smyth and Schillereff, 1982). These represent vestiges of the Iapetus Ocean (Williams, 1979) that were obducted westward during the Ordovician Taconian Orogeny (Williams and Stevens, 1974). The allochthonous rocks include slate, mélange and polydeformed mafic schist and form a laterally continuous, thin belt along the Doucers Valley fault complex. The ophiolitic Coney Head Complex (Williams, 1977), composed of tonalite–trondhjemite, minor gabbro and granite, is also included in the Southern White Bay Allochthon (Smyth and Schillereff, 1982).

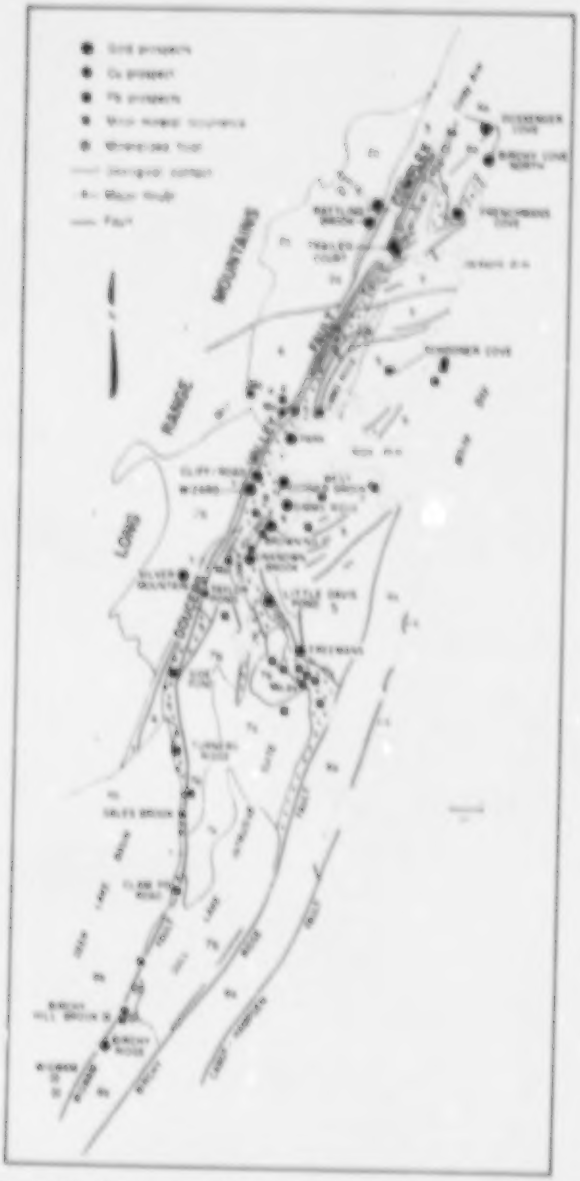
Silurian volcanic and sedimentary rocks of the Sops Arm Group unconformably or structurally overlie rocks of the Coney Arm Group and the Southern White Bay Allochthon. Within the Sops Arm Group, the Lower Volcanic formation and the Simms Ridge Formation host several gold occurrences (Figure 2). The Sops Arm Group dips moderately to the east and has been affected by west-directed thrusting that produced recumbent fold structures and a well-developed cleavage in the sedimentary units. It has been interpreted as one of several terrestrial caldera complexes formed during and after the final closure of Iapetus (Coyle and Strong, 1987).

The Sops Arm Group is intruded by the Devonian Gull Lake intrusive suite (Figure 2), which is made up of a variety of gabbroic to granitic rocks. The Devils Room granite, which intrudes the Long Range Inlier to the west of the Doucers Valley fault complex is included in the Gull Lake intrusive suite.

The youngest rocks in the area are the Carboniferous sediments of the Deer Lake Basin, which unconformably overlie or are faulted against the older rocks.

MINERALIZATION AND ALTERATION

The western White Bay area hosts three broad styles of mineralization:



LEGEND

UPPER PALEOZOIC (Basin-fill sequences and intrusions)

CARBONIFEROUS

8 **8a,** Anguille Group (Tournaisian): *greywacke, shale, minor sandstone and conglomerate;* **8b,** Deer Lake Group (Visean): *conglomerate, sandstone, siltstone*

DEVONIAN (ca. 398 Ma)

7 Gull Lake intrusive suite: **7a,** *intermediate and mafic intrusive rocks;* **7b,** *granite and trondhjemite*

6 Devils Room granite

SILURIAN

5 Sops Arm Group

LOWER PALEOZOIC ALLOCHTHON

CAMBRIAN – MIDDLE ORDOVICIAN

4 Southern White Bay Allochthon: *partially ophiolitic (mélange containing ultramafic blocks is cross-hatched);* **4a,** Coney Head Complex

LOWER PALEOZOIC AUTOCHTHON (Platform)

3 Coney Arm Group: *carbonate, shale, quartzite*

PRECAMBRIAN (Grenvillian basement)

MIDDLE PROTEROZOIC AND EARLIER

2 *Massive to foliated, feldspar-megacrystic, granitoid plutons;* **2a,** *Apsy pluton;* **2b,** *Main River pluton*

1 *Leucocratic gneiss, amphibolite, and gabbro*

Figure 2. *General geology and mineral occurrences in western White Bay. The Lower Volcanic formation and the Simms Ridge Formation of the Sops Arm Group are patterned. Compiled by Tuach (1987a) from mapping by Smyth and Schillereff (1981, 1982), Hyde (1982) and Erdmer (1986a,b).*

i) Structurally controlled mesothermal gold–base-metal mineralization occurs in the volcanic and sedimentary rocks of the Silurian Sops Arm Group (e.g., Browning Mine, Unknown Brook) as well as in Late Proterozoic granitoid rocks and unconformably overlying Eocambrian to Cambrian sediments (Rattling Brook and Silver Mountain) (Figure 2). Anomalous gold values have been found also, within the Murrays Cove schist and Coney Head Complex of the Southern White Bay Allochthon.

ii) Stratabound galena mineralization occurs in brecciated, altered dolostone of the Lower Volcanic formation at Turners Ridge and Side Pond (Figure 2).

iii) Minor fluorite and molybdenite are found in the granites and related aplitic dykes of the Gull Lake intrusive suite, which includes the Devils Room Granite (Figure 2).

GOLD MINERALIZATION

Gold mineralization is found in a variety of units of different rock types, ranging in age from Precambrian to at least as young as Silurian.

The most important deposit found to date is the Rattling Brook deposit and related peripheral showings (see Bruneau, 1984; French, 1985), hosted by Late Proterozoic altered granodiorite of the Apsy pluton and by unconformably overlying platformal sediments of the Coney Arm Group. Pyrite and arsenopyrite with associated gold are hosted by fractures, veinlets and shear zones and are disseminated within altered wallrock. Alteration minerals include K-feldspar, albite, ankerite, siderite and sericite. This mineralization has been previously extensively described in numerous assessment files and by Tuach and French (1986), McKenzie (1987b), Saunders and Tuach (1988). At the Silver Mountain showing, similar mineralization and alteration occur along faults within the Main River pluton (Figure 2). Here, gold values ranging between 100 and 5150 ppb have been found in pyrite-rich silica–carbonate–feldspar–sericite altered phases of the host granodiorite. Sporadic enrichments of chalcopyrite, galena and molybdenite, accompanied by pyrite and weakly anomalous gold, have also been found (French, 1987b).

Gold mineralization in the Rattling Brook area also occurs within Eocambrian to Cambrian platformal sediments of the Coney Arm Group that unconformably overly the mineralized granitoid. Minor gold mineralization occurs sporadically within the Coney Head Complex and the Murray's Cove schist of the Southern White Bay Allochthon.

The southern half of the Silurian Sops Arm Group is host to numerous gold occurrences that occur along shear zones. These are described more fully below.

Southern White Bay Allochthon

Carbonate alteration occurs intermittently over a distance of at least seven kilometres along the Doucers Valley fault complex. The alteration, which consists of Fe- and Mg-carbonate, sericite and green fuchsitic mica, is developed within sheared, chloritized slivers of mafic to ultramafic? rock within the Murray's Cove schist (O'Sullivan, 1986; Holmes *et al.*, 1988). Minor amounts of pyrite and arsenopyrite occur locally. The alteration zone has been extensively sampled but has returned only sporadic weakly anomalous (up to 450 ppb) gold values. At the Trailer Court occurrence (Figure 2), near the northeastern end of the alteration zone, a quartz, sericite, ankerite schist that contains minor pyrite, is exposed over a 120 m interval within chloritized mafic volcanics. The alteration here has been extensively chip- and channel-sampled (O'Sullivan, 1986; Tuach, 1986) but did not returned significant gold values. Near the other end of the alteration zone, about 6 km to the southwest, however, till concentrates have yielded several grains of visible gold and have returned gold values of up to 15.1 ppm (O'Sullivan, 1986).

Sporadic low-grade Au mineralization has been found in quartz–carbonate veins and localized pyritic shear zones that cut a variety of rock types in the Coney Head Complex. Quartz–carbonate veins, locally containing molybdenite, chalcopyrite and pyrite, cut gabbroic to tonalitic rocks along the western shore of White Bay (French, 1987a). Samples from these veins generally returned Au assays of <200 ppb, but a value of 4600 ppb Au over a 0.75 m width was returned from one quartz–carbonate vein on the coast (Birchy Cove North occurrence–MODS ref. 12H/15-Mo004). This vein also contains chalcopyrite, pyrite and about 0.5 percent molybdenite. Nearby swarms of sheeted leucocratic muscovite granite dykes contain disseminated pyrite and are cut by numerous quartz veins (Smyth and Schillereff, 1982). A 1.5-m-wide quartz–feldspar pegmatite, which cuts quartz gabbro about 150 m to the north, contains minor pyrite, chalcopyrite and molybdenite (Smyth and Schillereff, 1982). The mineralized pegmatite and the granite dykes may be genetically related to the gold–molybdenite-bearing quartz veins.

To the northwest of the above showing, numerous quartz–carbonate veins that contain galena ± pyrite cut a quartz–sericite schist unit that may be altered volcanic rock (French, 1987a). This schist has a maximum exposed width of 30 m and a strike length of 0.75 km along a northeast-trending fault zone. It contains finely disseminated pyrite and is host to silica–carbonate–potassium alteration similar to that seen at the Rattling Brook deposit (French, 1987a). A grab sample from a quartz–carbonate vein that cuts this schist at Dossenger Cove (MODS ref. 12H/15-Pb002) returned 5.4 percent Pb, 34 ppm Ag and about 170 ppb Au.

At the southern margin of the Coney Head Complex at Frenchmans Cove (MODS ref. 12H/15-Au002), a grab sample from a quartz–carbonate vein in a localized zone of pyrite-rich sheared granitoid has returned a value of 1800 ppb Au (O'Sullivan, 1986). This occurrence is also known as Jacksons Arm North (Tuach, 1990).

Sops Arm Group

Gold mineralization in the Sops Arm Group occurs in lode quartz veins in unaltered to strongly sericitized and carbonatized, altered volcanic and sedimentary rocks. The gold occurrences are concentrated in the Lower Volcanic and Simms Ridge formations and are generally found along or near shear zones (Figure 2). The quartz veins generally contain carbonate and minor to significant amounts of base metals (principally pyrite, chalcopyrite, galena and sphalerite); locally tourmaline or barite occur in the veins. The two main showings, which are located along a north–south-trending fault that runs along a small brook (Corner Brook), are the Unknown Brook prospect and the Browning Mine (a past producer of about 5.1 kg of Au). The other occurrences are generally small, or are characterized by sporadic Au concentrations, and are hosted by quartz veins or altered shear zones. These include the Simms Ridge, West Corner Brook, Road, Wizard and Freemans occurrences (Figure 2). Other small base-metal (i.e., pyrite, chalcopyrite, galena, sphalerite, bornite, malachite) occurrences and barite-bearing quartz veins are found in various units within the Sops Arm Group. Many of these are on file with the Newfoundland Department of Mines and Energy's Mineral Occurrence Data System, and may or may not have been assayed for Au or other metals.

A description of the more significant occurrences within the Sops Arm Group follows.

Unknown Brook Gold Prospect

At the Unknown Brook showing (MODS ref. 12H/10-Au005) gold is found in syn-deformational pyritic quartz–carbonate–potassium feldspar veins. These occur within a conglomerate bed at the top of the Lower Volcanic formation near the contact with the overlying Simms Ridge Formation and are above and parallel to a thrust plane (Figure 3) that is defined by a 15-m-thick zone of pervasive and intense sericite alteration (Tuach *et al.*, 1988). This was described as 'sheared, carbonatized and pyrophyllitized' by Snelgrove (1935). However, recent XRD analysis (Tuach and Saunders, *in preparation*) of three samples from this zone indicates only muscovite and quartz. Minor pyrite and narrow quartz–carbonate veins are also present in the alteration zone and siliceous, cigar-shaped rods surrounded by thin bands of sericite are ubiquitous (Plate 1). Previous workers have considered these rods to be deformed primary structures such as rhyolitic lithophysae or pyroclastic fragments. However, they may be tectonic lithons (formed by the intersection of anastomosing foliation seams) that were produced during movement along the thrust plane (B. O'Brien and J. Hayes, personal communications, 1990). Hayes and O'Driscoll (1990) described similar structures in pyrophyllitized and sericitized shear zones within the Harbour Main Group.

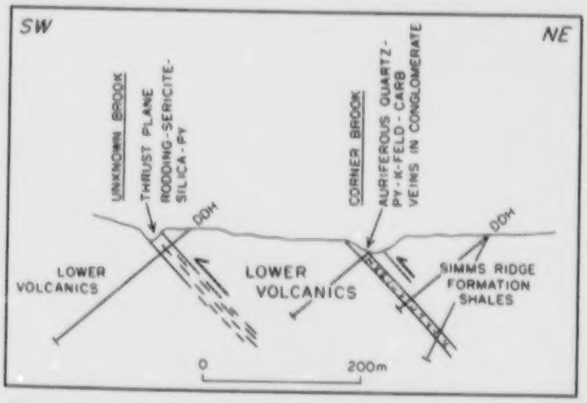

SW
NE
UNKNOWN BROOK
THRUST PLANE
RODDING-SERICITE-SILICA-PY
DDH
CORNER BROOK
AURIFEROUS QUARTZ-PY-K-FELD-CARB VEINS IN CONGLOMERATE
DDH
LOWER VOLCANICS
LOWER VOLCANICS
SIMMS RIDGE FORMATION SHALES
0
200m

Figure 3. *Schematic section of the geology in the vicinity of the Unknown Brook deposit, as defined by drilling by U.S. Borax Exploration. Gold-bearing quartz–potassium feldspar–pyrite veins occur in a conglomerate at the top of the Lower Volcanic formation. An underlying silica-sericite alteration zone is interpreted to represent a thrust plane. From Tuach* et al. *(1988) based on information provided by B. Mercer.*

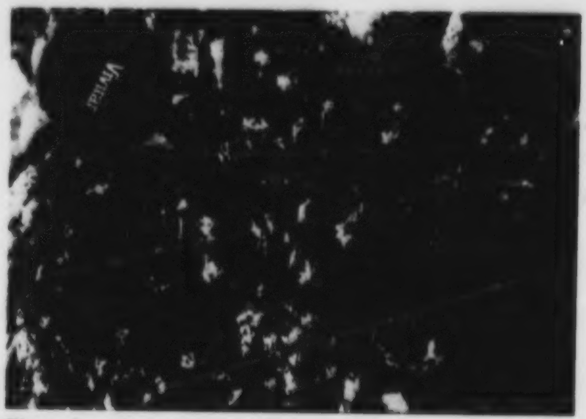


Plate 1. *Cigar-shaped siliceous rods in silica–sericite alteration zone at Unknown Brook. These structures may be tectonic lithons formed by the intersection of anastomosing foliation seams.*

The main gold zone is exposed at the junction of Unknown Brook and Corner Brook and for about 250 m upstream (Figure 2), where several lenticular, weakly deformed, auriferous, K-feldspar–quartz–carbonate–pyrite veins up to 25 cm wide cut the conglomerate (Tuach, 1987b). The veins also contain minor galena and fluorite and rare stibnite; the gold occurs as tiny inclusions of electrum (Au:Ag is 80:20) within galena (Burton, 1987).

Drilling in this area by U. S. Borax yielded the following intersections from four out of nineteen holes: 9.3 ppm Au over 1.74 m, 8.6 ppm Au over 2.59 m, 35.7 ppm Au over 0.33 m, and 78.9 ppm Au over 0.12 m; grab samples of vein material from outcrop have returned values of up to 85 ppm Au, 180 ppm Ag and 7450 ppm Pb (Burton, 1987).

Browning Mine

At the Browning Mine (MODS ref. 12H/10-Au001) deformed syn-deformational, or possibly pre-deformational, quartz veins occur in altered volcanic and sedimentary rocks of the Lower Volcanic and Simms Ridge formations (Tuach, 1987b).

This mine was the site of the first gold mining in Newfoundland in 1903. Approximately 149 troy ounces (5.1 kg) of Au were produced from 1000 tons of ore (Murray and Howley, 1918; Snelgrove, 1935). The rock was crushed in a stamp mill, and the gold recovered by use of a Wilfley table (Murray and Howley, 1918; Lundberg, 1936). The mine was developed in 1902 but by 1904 production had ceased as the high-grade ore was apparently exhausted. In 1936, the mine was partly dewatered and the workings mapped; several samples were taken with negative results (Lundberg, 1936).

The workings, described by Lundberg (1936) and Heyl (1937), consisted of three vertical shafts located on the east bank of Corner Brook. The southern shafts are approximately

70 m apart and were connected by an irregular sloping drift at a depth of about 20 m; another shaft is located about 200 m to the northeast. An adit runs from the east bank of the brook to the middle shaft. Material from the waste tips can be examined nearby.

Mineralization and alteration is located at the contact between mafic volcanics of the Lower Volcanic formation and foliated shales of the Simms Ridge Formation. The shales strike parallel to Corner Brook, about 025° and dip about 30° southeast (Snelgrove, 1935; Heyl, 1937); the underlying volcanics are essentially conformable. A low-angle east-dipping fault cuts through the shales near the contact with the underlying felsic volcanics and can be traced along or parallel to the brook for about 1 km (Heyl, 1937; McKenzie, 1985a). This fault generally parallels, but locally crosscuts, bedding; there appears to have been some rotational movement but the amount of displacement has probably not been great (Heyl, 1937). Where the fault outcrops beneath the adit, it is represented by a schistose, chloritic band, up to 1 m wide (Tuach, 1987b). Elsewhere, it is manifested only by an indistinct crushed zone (Heyl, 1937).

Shales above the fault are typically sericitic, carbonate spotted and locally pyritic and are cut by quartz–carbonate–sulphide veins up to 0.5 m thick (McKenzie, 1985a). The sericite alteration ('pyrophyllite' of Snelgrove, 1935) of the shales is locally very intensive; X-ray diffraction analysis of a sample of this alteration from upstream from the adit revealed muscovite, quartz and dolomite (Tuach and Saunders, *in preparation*). Smaller areas of alteration affect the shales and minor silicic tuff beds farther upstream.

The carbonate-spotting (see Tuach, 1987a, Plate 5) of the Simms Ridge shales is a regional feature and is ubiquitous south of Sops Arm. To the north of Sops Arm, these spots are absent and the Simms Ridge shales are apparently unaltered (O'Sullivan, 1986). These spots, which have been previously described as siderite by numerous workers, are in fact the result of partial to complete replacement of light-coloured carbonate crystal porphyroblasts by limonite during surface weathering. The XRD analysis of samples from the intense sericite alteration zone suggests the unweathered crystals are dolomite. They are locally flattened along the foliation of the host rock.

A unit of grey, massive, orange- to brown-weathering carbonate locally outcrops beneath the fault. This unit is 5 to 10 m thick, contains cherty lenses, and is characterized by fuchsite spots and disseminated galena and pyrite mineralization (McKenzie, 1985a; Tuach, 1987b). It is cut by narrow quartz–carbonate–galena veinlets and galena fills porosity within the rock (Plate 2). It grades into an underlying fuchsitic, pyritic, intensely carbonate-spotted unit that forms the base of the Simms Ridge Formation (Figure 4). The galena-rich carbonate zone may be the result of massive replacement of the host rock (McKenzie, 1985a) or it may be the altered equivalent to fossiliferous limestone beds at the base of the Simms Ridge Formation (these contain minor disseminated galena) that outcrop approximately 500 m upstream (Tuach, 1987b).

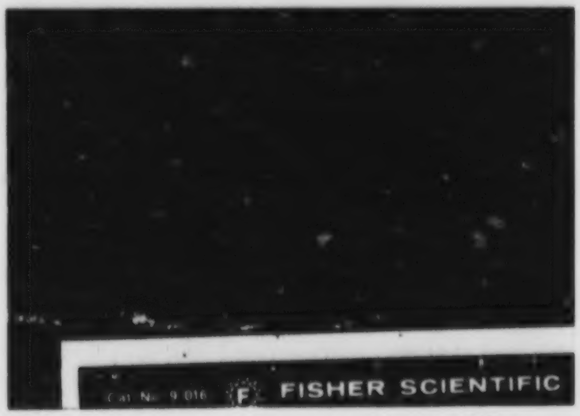


Plate 2. *Disseminated galena mineralization filling open spaces in massive carbonate unit at the Browning Mine.*

Quartz–carbonate veins are common in all the outcrops and locally contain sulphides and anomalous gold. They vary from boudinaged and tightly folded in the plane of the schistosity to crosscutting, post-deformational veins (Tuach, 1987b). Heyl (1937) reported that quartz lenses are most abundant within four feet of the low-angle fault, and that narrow quartz veins are also found along the fault plane. The quartz lenses are generally between 18 and 30 inches long and 3 and 9 inches thick, and strike parallel to bedding but dip more steeply (Heyl, 1937).

The mineralization as described by J. P. Howley in 1902 consisted of quartz vein-hosted pyrite, chalcopyrite, sphalerite, galena and minor specularite and pyrrhotite; gold appeared to be concentrated with the sphalerite and galena, but rare free gold as wire and nuggets in the quartz was also found. High silver values were also associated with the galena (Murray and Howley, 1918). Howley also reported that gold was panned from crushed wallrock and overlying soils as well as from vein material. Currently, minor pyrite, galena, chalcopyrite and sphalerite in deformed quartz veins are exposed in the blasted cut at the north end of the alteration zone (Tuach, 1987b). These mineralized veins may represent the ore horizon; a grab sample from a one-inch-wide chalcopyrite vein returned two analyses of more than 7000 ppb Au (Tuach and Saunders, *in preparation*).

In 1985 and 1986, BP-Selco Resources Limited carried out exploratory trenching and diamond drilling in the vicinity of the Browning Mine. Figure 4 shows a simplified cross-section based on data from two drillholes (McKenzie, 1985a, 1987a). A chip sample over a 3 m interval of shale cut by 5- to 10-cm quartz veins produced a gold assay of 740 ppb; a 0.4-m-wide quartz–carbonate–sulphide vein in a drillhole assayed 7.2 ppm Au and a 2-m-long section of brecciated, pyritic, felsic tuff cut by quartz–carbonate veins assayed 1.4 ppm Au. The fuchsitic carbonate unit was found to contain tens to hundreds of ppb Au (McKenzie, 1985a).

Trenching and drilling (2 holes) were also carried out at the newly discovered Browning West showing about 1 km

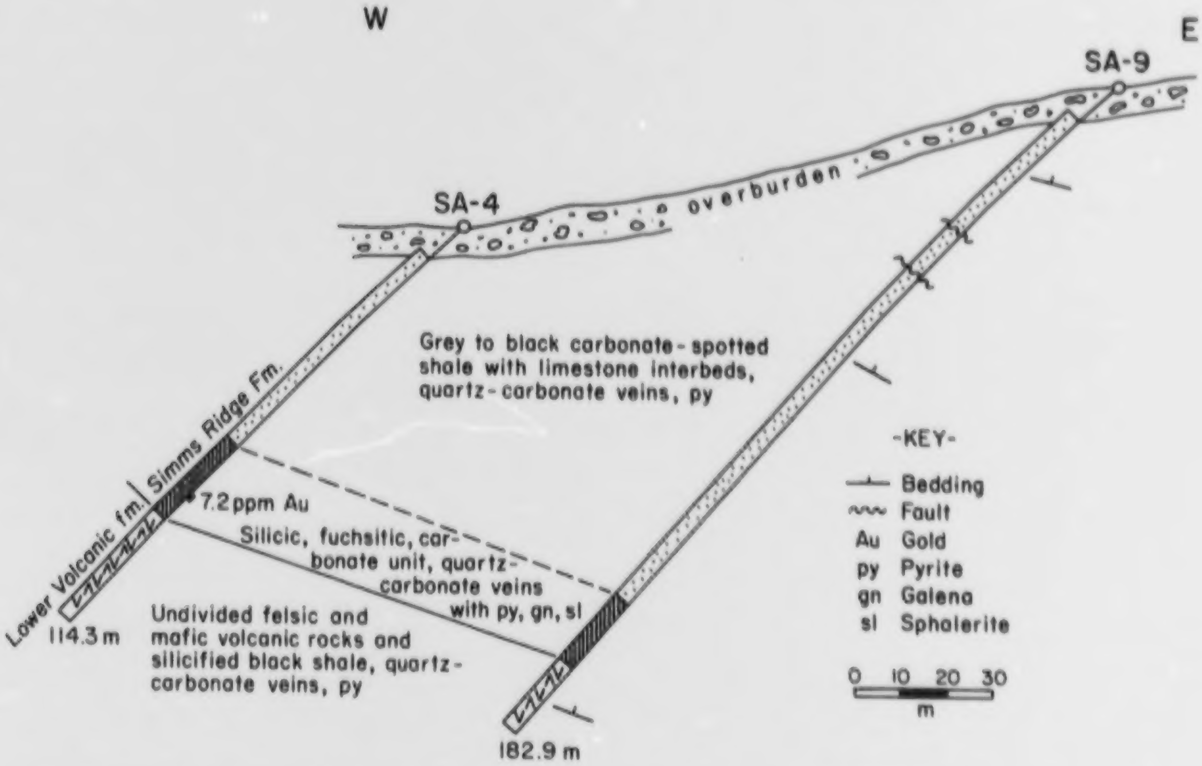

W
E
SA-9
SA-4
overburden
Grey to black carbonate-spotted shale with limestone interbeds, quartz-carbonate veins, py
Simms Ridge Fm.
Lower Volcanic fm.
7.2 ppm Au
Silicic, fuchsitic, carbonate unit, quartz-carbonate veins with py, gn, sl
Undivided felsic and mafic volcanic rocks and silicified black shale, quartz-carbonate veins, py
114.3 m
182.9 m
-KEY-
Bedding
Fault
Au Gold
py Pyrite
gn Galena
sl Sphalerite
0 10 20 30
m

Figure 4. *Simplified cross section through two drillholes from the Browning Mine area. From McKenzie (1985a, 1987a). The contact between the silicic, fuchsitic, carbonate unit (dashed line) is in places a low-angle, semi-conformable fault, below which a 5- to 10-m-thick, massive, galena-bearing, carbonate unit occurs locally in surface exposures.*

due west of the Browning Mine. The drillholes intersected brecciated, carbonatized and sericitized felsic volcanics. A 2-m-long section of core containing a 10-cm-wide quartz–carbonate–pyrite vein assayed 2670 ppb Au. A random chip sample of vein quartz from throughout a similarly altered and mineralized trench assayed 4850 ppb Au (McKenzie, 1986).

Other Gold Occurrences in the Sops Arm Group

Auriferous deformed quartz veins cut volcanic rocks of the Lower Volcanic formation along the Doucers valley fault complex. At the Wizard showing (MODS ref. 12H/10-Au006) (Figure 2) strongly foliated, sericitic schist is developed within felsic tuff near the contact with overlying chloritic mafic volcanics (O'Sullivan, 1986). The sericitic zone contains disrupted and tightly folded 3- to 30-cm-wide quartz veins that locally make up 60 percent of the section. The quartz veins contain minor pyrite and tourmaline, and traces of galena and have returned gold values of 5300 and 6150 ppb from grab samples and 2300 ppb over a 2.4 m channel sample (O'Sullivan, 1986; Tuach and Saunders, *in preparation*). Drilling by Esso Minerals Limited has traced the zone of quartz veining for a strike length of 285 m and to a depth of 50 m. The best drill results were 1700 ppb over 0.7 m and 1000 ppb over 0.8 m from two closely spaced (15 m) holes—one down-dip from the other (O'Sullivan, 1986). To the north, at the Road showing or Sops Arm Road showing (MODS ref. 12H/10-Au008) (Figure 2) and the nearby Cliff Zone occurrence (MODS ref. 12H/10-Au007), auriferous quartz veins and shear zones cut brecciated tuff of the Lower Volcanic formation over a strike length of at least 1 km. Minor pyrite, galena, chalcopyrite and barite occur locally in the veins. The host rock is variably chloritized, sericitized and carbonatized. Gold values of up to 3650 ppb from grab samples (O'Sullivan, 1986) and 990 ppb from chip samples (McKenzie, 1985b; Tuach, 1990) have been identified. These outcrops are on or near faults of the Doucers Valley fault complex, and are severely deformed and schistose. The deformation of the quartz veins and the development of local areas of intense brecciation and 'gouge' in these exposures is probably due to movement along the Doucers Valley fault complex during the Carboniferous, and these features have been superimposed on earlier more ductile deformation features (Tuach, 1987b).

The Park Prospect (MODS refs. 12H/15-Pyr009 and -Pyr010) (Figure 2), includes several small occurrences (Tuach, 1986). A 020°-trending, 30-cm-wide vertical pyrite-bearing quartz vein and several smaller veins cut sericitized tuff of the Lower Volcanic formation over a 20 m distance in a roadcut. A similarly trending, 3-m-long, galena-bearing quartz vein occurs about 25 m west of the road. Chips from the galena-bearing vein returned Au values of 2730 ppb and chips from a quartz–pyrite vein on the road returned Au values of 203 and 541 ppb. Plate 3 shows galena with associated gold in a sample from this occurrence. A similar style of mineralization outcrops over a 30 m² area in a nearby quarry. Mineralization consists of stringer pyrite, minor chalcocite and chalcopyrite in narrow quartz veins cutting rhyolitic tuff. Chips from this outcrop returned Au values of 120 ppb.

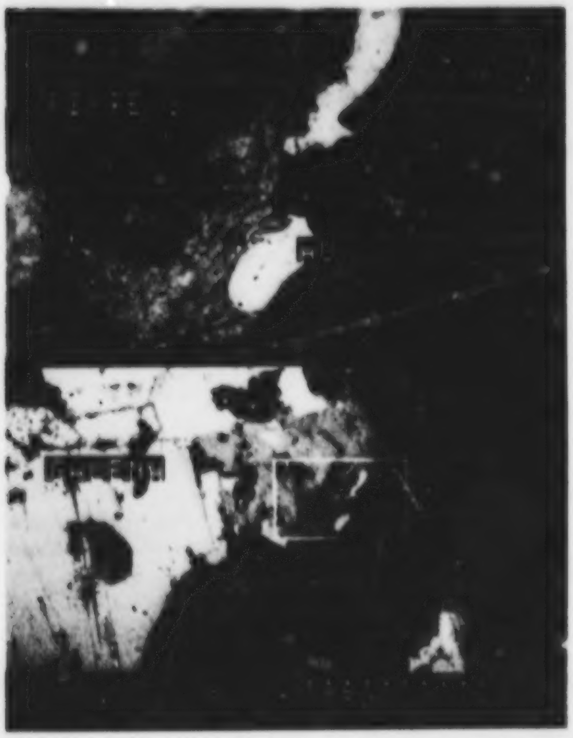


Plate 3. *Gold on rim of galena grain in quartz–pyrite vein, which is one of several mineralized veins that cut tuffs of the Lower Volcanic formation at the Park Prospects. Scanning electron photomicrograph (top is 5x bottom). The larger gold grain is 30 microns long.*

The West Corner Brook prospect (MODS ref. 12H/10-Au002) was the first discovered gold occurrence in the Sops Arm area. It was staked in 1898 by J.M. Jackman and a 19-m-long adit, a shallow shaft and several test pits and trenches were excavated at three localities. The following description of this showing was provided by D. Wilton (personal communication, 1990). An intense network of ramifying quartz ± carbonate veins cuts rhyolite porphyry and tuff of the Sops Arm Group. Some of the larger veins are sigmoidal. The veins and, to a lesser extent, the wallrock, contain clots of pyrite, and minor galena, chalcopyrite and sphalerite; specularite is common in the larger veins. The fresh rhyolite is purplish, but intensive hematization has locally imparted a pinkish colour. The rhyolite is also variably sericitized and is locally fractured and brecciated. Snelgrove (1935) assayed three grab samples from mineralized veins; the highest results were about 4400 ppb Au and 63 ppm Ag from a pyritic quartz vein. Grab samples of vein material assayed up to 1 ppm Au.

The Simms Ridge Prospect (MODS ref. 12H/10-Au003) was discovered in 1933 and by 1936 nineteen trenches and a shallow shaft had been excavated. Snelgrove (1935) visited the area during trenching and Heyl (1937) provided a detailed trench map. The trenches were excavated to explore a 150-m-long northeast-trending zone of irregular and lenticular quartz veins that cut shales of the Simms Ridge Formation and also cut a pretectonic felsite dyke (Unit 22 of Smyth and Schillereff, 1982) that intrudes the shales. The shales exhibit the typical carbonate-spotting and fuchsitic alteration (see above) and both the shales and the felsite are variably sericitized and locally contain disseminated pyrite. Individual quartz veins are up to 5 m thick, and contain sporadic disseminated to fist-sized bunches of sulphides (mainly pyrite, chalcopyrite and galena). Snelgrove (1935) reported visible native gold associated with the galena and confirmed this with microscopic study. He also reported an assay of 5 ozs., 4 dwts., 12.8 grs. Au (about 180 ppm) and 47 ozs., 19.2 grs. Ag (about 1600 ppm) from a selected sample of weathered galena; ten channel samples, however, returned values of nil to 1.7 ppm Au. Lundberg (1936) reported an average grade of 0.04 oz/t (1.37 ppm) Au from 43 samples taken by a variety of methods (grab, chip, channel and bulk sampling). More recently, four grab samples from two trenches returned values between 0.23 and 0.87 oz/t (7.8 and 29.6 ppm) Au (O'Sullivan, 1981) and five samples from a large quartz vein at the showing returned Au values between 340 and 1150 ppb (McKenzie, 1985b). The gold values, however, are erratic and spotty and a significant deposit has not been outlined. The association of gold with galena is seen in other occurrences in the area (e.g., the Park Prospect, Plate 3).

The Freemans prospects (MODS ref. 12H/10-Au004) were discovered and trenched in 1935. Narrow quartz–carbonate veins cut clastic and carbonate sediments of the Simms Ridge Formation. Minor amounts of pyrite and chalcopyrite occur in the veins and disseminated pyrite, chalcopyrite, galena and sphalerite are locally present in the carbonate beds (Heyl, 1937; McKenzie, 1986). Locally, fine black needles of tourmaline are found in the quartz veins (Heyl, 1937). A sample of mineralized limestone returned a Au value of about 4.3 ppm (Heyl, 1937). BP-Selco Resources Limited resampled the old trenches in 1986, but reported only sporadic Au values of less than 100 ppb and a Cu value of about 0.5 percent (McKenzie, 1986).

Similar mineralization occurs about 3.5 km to the northwest near Little Davis Pond, in proximity to, and within the Big Davis Pond granite, a small high level stock that is part of the Gull Lake intrusive suite. This mineralization was discovered and sampled by BP-Selco Resources Limited (McKenzie, 1986, 1988). Samples from a 25-cm-wide quartz–pyrite vein that cuts the granite returned assays of 0.65 and 0.42 oz/t (22.3 and 14.4 ppm) Au, and were found to contain anomalous Ag, Bi, Pb and W. Two nearby quartz–pyrite–arsenopyrite–fluorite veins returned values of less than 40 ppb Au. The wallrock to the veins was not found to be mineralized. The surrounding carbonate member of the Simms Ridge Formation is cut by an extensive quartz–carbonate veinlet stockwork that locally contains pyrite, galena, chalcopyrite, sphalerite, fluorite, and malachite (MODS ref. 12H/10-Pyr020). A sample of this mineralization returned a value of 1900 ppb Au, >200 ppm Ag, 774 ppm Bi and more than 1 percent each of Cu and Pb; another sample returned a value of more than 1 percent Zn and a third assayed 570 ppb Au (McKenzie, 1986, 1988).

Mineralized (pyrite, galena, chalcopyrite) quartz veins cut a quartz monzonite sill within the Natlins Cove Formation at Schooner Cove (MODS ref. 12H/15-Ag001). Two selected sulphide-rich samples gave anomalous Ag (69 and 45 ppm) but no gold (Snelgrove, 1935).

STRATABOUND CARBONATE-HOSTED LEAD MINERALIZATION

Significant galena mineralization occurs in altered brecciated dolostone of the Lower Volcanic formation (Plate 4). In this unit, mineralization occurs sporadically over a distance of 15 km. Two main concentrations of mineralization, the Turners Ridge (MODS ref. 12H/11-Pb001) and Side Pond (MODS ref. 12H/11-Pb002) deposits, and several smaller occurrences, e.g., Gales Brook (MODS ref. 12H/10-Pb001) and Taylor Pond (MODS ref. 12H/10-Pb003) have been outlined by mapping and drilling (Dimmell, 1979; Mercer, 1986). Minor galena mineralization is also found in the surrounding felsic volcanics of the Lower Volcanic formation.

Plate 4. *Galena forms matrix to brecciated dolostone of the Lower Volcanic formation at Turners Ridge. Vertical distance about two metres.*

The Turners Ridge deposit contains approximately 200,000 tonnes of 3 to 4 percent lead; a schematic section through the deposit (Dimmell, 1979) is shown in Figure 5. The grey-green rock is predominantly severely brecciated dolostone characterized by local pervasive calcite alteration. Breccia fragments are generally angular and are commonly non-rotated, but where brecciation is very intense, fragments are fine-grained, rounded and corroded by calcite. Coarse- to fine-grained galena accompanied by calcite and minor barite, silica, pyrite and sphalerite occurs in fractures and fracture stockworks (Plate 4; Tuach, 1987a, Plate 6). The calcite has corroded and replaced rims of dolostone fragments. Brecciation, mineralization and calcite alteration are most intense at the Turners Ridge deposit, and not as well-developed at the Side Pond showing to the north, where mineralization is generally restricted to irregular veins.

Drilling has shown that the Silurian dolostone and rhyolite have been thrust westward over coarse, relatively undeformed conglomerate of the Carboniferous North Brook Formation (Figure 5), and additional (contemporaneous?) low-angle thrusts may occur in the Silurian volcanic rocks. For example, at the Turners Ridge deposit rusty-weathering, buff to pink, severely brecciated rhyolite of the Lower Volcanic formation has been locally thrust over the dolostone (Plate 5). These low-angle thrusts may represent localized, late movements on the adjacent Wigwam Fault (Tuach, 1987b). Minor galena mineralization occurs in the brecciated rhyolite near its contact with the dolostone, indicating that mineralization postdates the thrust faulting and is at least as young as Carboniferous.

FLUORITE AND MOLYBDENITE

Smyth and Schillereff (1982) reported minor fluorite and pyrite occurrences in the Moose Lake granite and Dunford (1984) reported fluorite occurrences in the Devils Room granite. In the latter, it occurs as fracture coatings and in the matrix of a 1-m-wide tuffisite zone (Tuach, 1986).

Minor coarse-grained molybdenite is found in granite pegmatite, quartz veins and pods within the Gull Pond granite and traces of molybdenite occur in small quartz veins in the Devils Room granite (Tuach, 1987a). Molybdenite mineralization also occurs in aplite dykes that cut the Gull Pond granite, the Black Duck Ponds trondhjemite and the Sops Arm Group in the Gull Pond Brook area (Dimmell, 1979). Many of these occurrences are listed with the Mineral Occurrence Data System of the Newfoundland Department of Mines and Energy (MODS ref. 12H/10-Mo001-008 and 12H/15-Mo002/003). Assays of mineralized aplite float returned values as high as 1.8 percent Mo and a quartz–aplite vein containing pyrite, chalcopyrite and a grey metallic mineral returned an analysis of 0.37 oz/t (12.7 ppm) Ag (Dimmell, 1979). Dimmell (1979) also reported silt sample analyses in excess of 1000 ppm Mo, 600 ppm Pb, 500 ppm U and 60 ppm WO3 from areas underlain by the Gull Lake intrusive suite.

DISCUSSION AND CONCLUSIONS

On a regional scale, there is an apparent spatial relationship between the Doucers Valley fault complex and

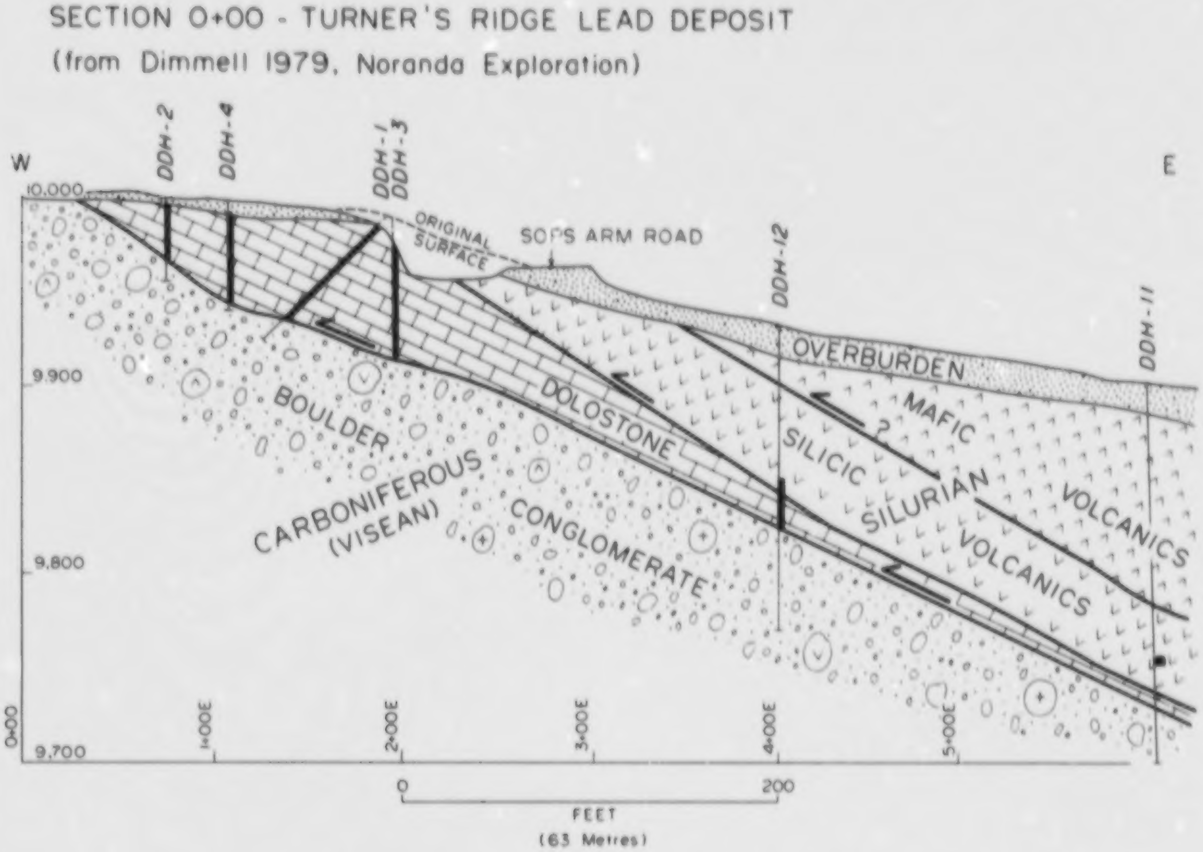

SECTION 0+00 - TURNER'S RIDGE LEAD DEPOSIT
(from Dimmell 1979, Noranda Exploration)
W
E
DDH-2
DDH-4
DDH-1
DDH-3
DDH-12
DDH-11
10,000
9,900
9,800
9,700
ORIGINAL SURFACE
SOPS ARM ROAD
OVERBURDEN
MAFIC
?
SILURIAN
VOLCANICS
SILICIC
VOLCANICS
DOLOSTONE
BOULDER
CARBONIFEROUS
(VISEAN)
CONGLOMERATE
0+00
1+00E
2+00E
3+00E
4+00E
5+00E
0
200
FEET
(63 Metres)

Figure 5. *West-east drill section across the Turners Ridge lead prospect. Mineralized portions of drill core are indicated by thicker lines. From Tuach (1987a) after Dimmell (1979).*

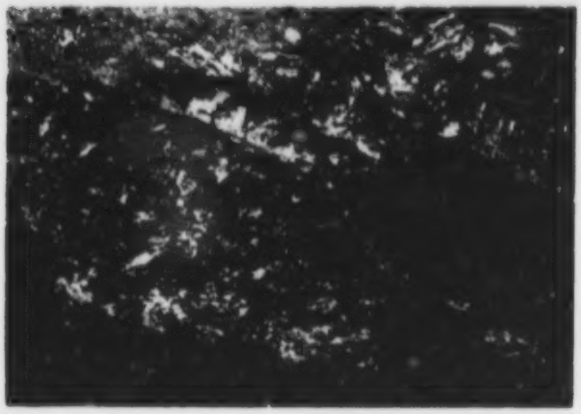


Plate 5. *Rhyolite thrust over galena-bearing brecciated dolostone at the Turners Ridge deposit. Both units are members of the Silurian Lower Volcanic formation.*

gold occurrences in the western White Bay area. Mineralization is hosted by a variety of rock types and is generally confined to veins and fracture stockworks, and as such, is clearly epigenetic. Davenport and McConnell (1988) have shown that elements such as As and Sb are enriched in lake-sediment samples on a regional scale in the Baie Verte–White Bay area. Areas of enrichment are associated with gold occurrences and major lineaments (e.g., the Doucers Valley fault complex and the Baie Verte Lineament) and indicate that hydrothermal systems were operative on a regional scale. Therefore, it is possible that all the gold occurrences in the western White Bay area formed from a single widespread mineralizing event. The Doucers Valley fault complex and subsidiary structures may have provided a conduit along which hydrothermal fluids circulated. Tuach *et al.* (1988) suggested that the ubiquitous carbonate porphyroblasts that occur in much of the Silurian Simms Ridge Formation are the product of hydrothermal alteration and their distribution outlines the areal extent of hydrothermal systems in Silurian rocks of the White Bay area.

There is some evidence that gold mineralization in the Sops Arm Group ranges from syn- (or possibly pre-) deformational to post-deformational with respect to Late Silurian thrusting (Tuach, 1987a,b). For example, at the Browning Mine there is a variation from boudinaged and tightly folded to crosscutting post-deformational quartz–carbonate veins. Veins at the Simms Ridge and Unknown

Brook occurrences are boudinaged, but those at the West Corner Brook prospect are mostly post-deformational. Mineralization is apparently structurally controlled to the extent that fault gouge planes and permeable shear zones, as well as areas of tensional fracturing, appear to have provided pathways for fluid flow and open spaces for mineral deposition.

The Rattling Brook deposit has many of the characteristics of mesothermal gold deposits, including high As, high Au/Ag ratios, high CO_2 contents in fluid inclusions, and intermediate pH alteration assemblages.

The gold showings in the Sops Arm Group may have resulted from the same mineralizing event that formed the Rattling Brook gold deposit. Tuach *et al.* (1988) pointed out that the presence of ductile thrust zones in less competent rocks, and tensional mineralized veins in more competent rocks, suggests a depth of vein formation in excess of 3 km, contradicting earlier suggestions that the alteration and mineralization in the Sops Arm Group resulted from epithermal processes. In addition, CO_2-rich fluid inclusions have been observed in quartz veins from the Browning, Sops Arm Road and Park showings (Tuach and Saunders, *in preparation*), and are typical of mesothermal rather than epithermal deposits (Nesbitt *et al.*, 1986).

The alteration assemblages found around many of the occurrences include carbonate, fuchsitic mica, and sericite. Although pyrophyllite has been reported from some occurrences (cf. Snelgrove, 1935; O'Sullivan, 1986; McKenzie, 1986) it has not been conclusively identified. X-ray diffraction of 'pyrophyllite' from the Unknown Brook occurrence and the Browning Mine showed only sericite.

At Rattling Brook, gold occurs in pyrite and apparently is also associated with arsenopyrite (there is a positive Au:As association). There is little enrichment of base metals. Pyrite and arsenopyrite and locally gold are also found in alteration zones within the Murray's Cove schist. However, in the Sops Arm Group gold is apparently associated with galena; Cu and Zn are locally enriched and As is not significantly enriched. Such contrasts in metal content may result from regional elemental zonation and could reflect local variations in host-rock composition or fluid composition, pressure or temperature.

Differences in alteration styles may relate to the wall-rock composition, which has a direct effect on the mineralogy of the resulting alteration assemblage (cf. Phillips and Brown, 1987; Colvine *et al.*, 1984). For instance Böhlke (1989) found that disseminated sulphide mineralization formed in granite wall rock, and carbonate alteration formed in ultramafic rock affected by the same mineralizing fluid. This could explain the differences in alteration associated with gold–pyrite–arsenopyrite mineralization in the Murray's Cove schist and Apsy pluton (Rattling Brook deposit).

It has been suggested (Tuach and Saunders, *in preparation*) that the Gull Lake intrusive suite may have provided the heat necessary for circulation of gold-bearing hydrothermal fluids within the rock column, and as well may have been a partial fluid source. A more direct genetic link, i.e., formation of gold mineralization within the Sops Arm Group by magmatic–hydrothermal processes, does not seem likely in the apparent absence of large-scale hydrothermal alteration within the Gull Lake intrusive suite and the general lack of granophile element (Mo, F, W) enrichment in the gold-bearing quartz veins. The mineralized veins within and adjacent to the Big Davis Pond granite are somewhat of an exception in that they contain fluorite and are locally enriched in W and Bi. To the north, gold-bearing veins within the Coney Head Complex contain significant molybdenite (e.g., Birchy Cove occurrence) and may be genetically related to nearby leucocratic muscovite granite dykes and molybdenite-bearing quartz–feldspar pegmatites. Such localized enrichments in granophile elements could result from either a direct magmatic–hydrothermal input, or by remobilization of these elements from older granite source rocks by leaching and reprecipitation by hydrothermal fluids.

The minor molybdenite and fluorite mineralization within the Gull Lake intrusive suite and related aplitic dykes is the result of late-stage magmatic processes and is probably not directly related to the gold mineralization in the White Bay area.

The galena mineralization at Turners Ridge and related showings is not enriched in gold and appears to be completely unrelated to the mesothermal gold mineralization in the White Bay area. The mineralization postdates the thrusting of the hanging-wall rhyolite over the host dolostone, indicating a relatively young age. The Carboniferous Deer Lake Basin to the south is a possible source of the Turners Ridge mineralization. The brecciated dolostone of the Lower Volcanic formation may have acted as a structural and chemical trap for upwelling lead-rich basinal fluids. Carboniferous carbonate rocks on the Port au Port Peninsula also host galena mineralization that is accompanied by calcite and barite gangue.

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REFERENCES

Bruneau, Y.

1984: Report on work done on Licence 2291 from May 30 to October 26, 1983. Labrador Mining and Exploration Company Limited, unpublished report, 15 pages. [12H/15(827)]

Böhlke, J.K.

1989: Comparison of metasomatic reactions between a common CO_2-rich vein fluid and diverse wall rocks: intensive variables, mass transfers, and Au mineralization at Alleghany, California. Economic Geology, Volume 84, pages 291-327.

Burton, W.B.
1987: Geological and diamond drilling report for mining claims 57 to 62, Sops Arm, Newfoundland. U.S. Borax Exploration, unpublished report, 104 pages. [12H/10(973)]

Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, A.J., Lavigne, M.F. Jr., Macdonald, A.J., Marmont, S., Poulsen, K.H., Springer, J.C. and Troop, D.G.
1984: An integrated model for the origin of Archean lode gold deposits. Ontario Geological Survey, Open File 5524, 98 pages.

Coyle, M. and Strong, D.F.
1987: Geology of the Springdale Group: a newly recognized Silurian epicontinental-type caldera in Newfoundland. Canadian Journal of Earth Sciences, Volume 24, pages 1135-1148.

Davenport, P.H. and McConnell, J.W.
1988: Lake sediment geochemistry in regional exploration for gold. *In* Prospecting in Areas of Glaciated Terrain—1988. *Edited by* D.R MacDonald and K.A. Mills. Canadian Institute of Mining and Metallurgy, Geology Division publication, pages 333-356.

Dimmell, P.M.
1979: Report on 1979 work, Noranda—Brinex joint venture, Sops Arm—White Bay Concession. Noranda Exploration, unpublished report, 59 pages. [12H(565)]

Dunford, W.T.
1984: Geology of the Devils Room Granite. Unpublished B.Sc. thesis, Memorial University of Newfoundland, 121 pages.

Erdmer, P.
1986a: Geology of the Long Range Inlier in the Sandy Lake map area, western Newfoundland. *In* Current Research. Part B. Geological Survey of Canada, Paper 86-1B, pages 19-29.

1986b: Geology of the Long Range Inlier in the Sandy Lake map area (12H), western Newfoundland. Geological Survey of Canada, Open File Map 1310.

French, V.A.
1985: Report on 1984 Exploration, Jackson's Arm Project, Licence No. 2291 and 2468. Labrador Mining and Exploration Company Limited, unpublished report, 146 pages. [12H/15 (910)]

1987a: First year assessment report on prospecting and geochemical exploration for Licence 2720 on claim block 4353 in the Coney Head area, Newfoundland. Shear Exploration Limited, unpublished report, 15 pages. [12H/15 (949)]

1987b: First year assessment report on geological and geochemical exploration for Licences 2831 and 2836 in the Silver Mountain area, northwestern Newfoundland. Shear Exploration Limited, unpublished report, 77 pages. [12H (955)]

Hayes, J.P. and O'Driscoll, C.F.
1990: Regional geological setting and alteration within the eastern Avalon high-alumina belt, Avalon Peninsula, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 145-155.

Heyl, G.R.
1937: The geology of the Sops Arm area, White Bay, Newfoundland. Newfoundland Department of Natural Resources, Geology Section, Bulletin 8, 42 pages.

Holmes, J.M., Gubins, A. and Oneschuk, D.
1988: Third year assessment report on geological, geochemical and geophysical exploration for the Sops Arm project for licence 2667 on claims in the Long Pond and Doucers Brook areas, Newfoundland. BP Resources Canada Limited, unpublished report, 70 pages. [12H/10 (1032)]

Hyde, R.S.
1979: Geology of the Carboniferous strata in portions of the Deer Lake Basin, western Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 79-6, 43 pages.

1982: Geology of the Carboniferous Deer Lake Basin. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 82-7.

Lock, B.E.
1969: Silurian rocks of western White Bay area, Newfoundland. *In* North Atlantic Geology and Continental Drift. *Edited by* M. Kay. American Association of Petroleum Geologists, Memoir 13, pages 433-442.

1972: Lower Paleozoic history of a critical area; eastern margin of the St. Lawrence Platform in White Bay, Newfoundland, Canada. 24th International Geological Congress, Montreal, Section 6, pages 310-324.

Lundberg, H.
1936: Compilation of reports on Sops Arm gold prospects, 1935-36. Hans Lundberg Limited, unpublished report, 27 pages. [12H/15 (13)]

McKenzie, C.B.
1985a: Second year assessment report on geological, geochemical and diamond drilling exploration for the Sops Arm Project for Licence 2427 on property in the Corner Brook area, southwestern Newfoundland. BP Resources Canada Limited, unpublished report, 64 pages. [12H/10 (929)]

1985b: First year assessment report on geological, geochemical and diamond drilling exploration for Licence 2522 on claim blocks 3304-3309 in the Sops Arm Area Newfoundland. BP Resources Canada Limited, unpublished report, 138 pages. [12H/10 (931)]

1986: Second year assessment report on geological, geochemical, diamond drilling and trenching exploration for Licence 2522 on claim blocks 3304-3309 in the Sops Arm area, Newfoundland. BP Resources Canada Limited, unpublished report, 118 pages. [12H/10 (964)]

1987a: Third year assessment report on trenching and diamond drilling exploration for the Sops Arm project for Licence 2427 on claims in the Corner Brook area, northwestern Newfoundland. Selco Division–BP Resources Canada Limited, unpublished report, 32 pages. [12H/10 (967)]

1987b: The Rattling Brook project: An exploration update. Unpublished manuscript presented to the Newfoundland Branch, Canadian Institute of Mining and Metallurgy, Nov. 5, 1987, 12 pages. [12H/15 (953)]

1988: Third year assessment report on geochemical, geophysical and trenching exploration for the Sops Arm Project for Licences 2522 and 2549 on claims in the Little Davis Pond area, northern Newfoundland. B.P. Resources Canada Limited, unpublished report, 22 pages. [12H/10 (996)]

Mercer, B.J.
1986: First year assessment report on diamond drilling for Licence 2666 on claim block 4303 in the Taylors Pond area, Newfoundland. U.S. Borax, unpublished report, 27 pages. [12H/10 (937)]

Murray, A. and Howley, J.P.
1918: Reports of Geological Survey of Newfoundland from 1881 to 1909. Robinson and Company Limited Press, St. John's, 725 pages.

Nesbitt, B.E., Murowchick, J.B. and Nuehlenbachs, K.
1986: Dual origin of lode gold deposits in the Canadian cordillera. Geology, Volume 14, pages 500-509.

O'Sullivan, J.R.
1981: Report on geological, geochemical and geophysical surveys carried out on part of the Brinco concession area, Sops Arm, Newfoundland. Esso Minerals Canada, unpublished report, 19 pages. [12H (787)]

1986: First year assessment report on prospecting, geological, geochemical, geophysical, trenching and diamond drilling exploration on properties in the White Bay area. Esso Minerals Canada, unpublished report, 186 pages. [12H (940)]

Phillips, G.N. and Brown I.J.
1987: Host rock and fluid control on carbonate assemblages in the Golden Mile Dolerite, Kalgoorlie gold deposit, Australia. Canadian Mineralogist, Volume 25, pages 265-273.

Saunders, C.M. and Tuach, J.
1988: K-feldspathization, albitization and gold mineralization in granitoid rocks: the Rattling Brook alteration system, western White Bay, Newfoundland. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 307-317.

Smyth, W R. and Schillereff, H.S.
1981: 1:25,000 geology field maps of Jackson's Arm northwest (Map 81-109), Jackson's Arm southwest (Map 81-110), Hampden northwest (Map 81-111), and Hampden southwest (Map 81-112). Newfoundland Department of Mines and Energy, Mineral Development Division.

1982: The Pre-Carboniferous geology of southwest White Bay. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-1, pages 78-98.

Snelgrove, A.K.
1935: Geology of gold deposits of Newfoundland. Newfoundland Department of Natural Resources, Geological Section Bulletin 2, pages 37-44.

Tuach, J.
1986: Metallogeny of Newfoundland granites–studies in the western White Bay area and on the southwest coast. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 27-38.

1987a: Mineralized environments, metallogenesis, and the Doucers Valley Fault Complex, western White Bay: a philosophy for gold exploration in Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 129-144.

1987b: Stratigraphy, structure and mineralization in western White Bay: a road log and field guide for the fall meeting of the Geological Association of Canada–Newfoundland Branch, 19 pages.

1990: A list of gold occurrences and deposits in Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey Branch, 72 pages. [NFLD (1928)]

Tuach, J. and French, V.A.
1986: Gold mineralization of possible late Precambrian age in the Jackson's Arm area (12H/15), White Bay, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 39-49.

Note: Geological Survey Branch file numbers are included in square brackets.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 349-[illegible]

MINERAL EXPLORATION OPPORTUNITIES IN LABRADOR —A PERSPECTIVE FOR THE 1990'S

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ABSTRACT

Despite its vast extent and geological diversity, Labrador has not been explored to the extent of equivalent areas of the Canadian Shield to the west. However, a substantial improvement in the geoscientific database for Labrador has been wrought by almost 20 years of work, mainly funded by four successive Canada–Newfoundland Mineral Development Agreements. The results of these geoscience programs, including regional mapping, metallogeny, Quaternary geology, geochemistry and geophysics have substantially changed our understanding of the broad framework and many of the details of Labrador geology. New geological provinces have been recognized and the boundaries of the previously recognized provinces refined, previously unknown orogenies have been discovered, and the accretionary history of the eastern part of the North American Shield has been documented.

To the end of 1990, approximately 56 percent of Labrador has been mapped at 1:100,000 scale. This mapping has, in some areas, identified geological environments where a significant economic potential can be postulated but where no deposits are known. Elsewhere, there remain large areas where geological mapping may identify significant new mineral potential. Reconnaissance lake-sediment sampling is complete for Labrador and the suite of elements mapped is being expanded.

The improved geological understanding has produced a new generation of genetic models for known mineral deposits and enhanced metallogenic interpretations. Exploration targets for mineral-resource development have been identified including: 1) Cu–Ni(PGE) and Cu–Zn polymetallic massive sulphides and structurally hosted mesothermal gold in Archean greenstone belts; 2) lode gold in a variety of settings including eastern Superior Province high-grade terranes, major fault zones in the Labrador Trough, Central Mineral Belt, and Grenville Province; 3) clastic sediment-hosted exhalative massive sulphides in Lower Proterozoic basins in the Nain, Churchill, Makkovik and Grenville provinces; 4) Proterozoic volcanogenic massive sulphides in the Churchill Province; 5) PGE deposits associated with a wide variety of intrusive environments; 6) granophile elements associated with orogenic and anorogenic intrusions; and 7) industrial minerals of many types in a wide variety of geological settings.

INTRODUCTION

Labrador is a vast territory lying on the eastern edge of the Canadian Shield (Figure 1). It covers more than 250,000 km², and extends from the Str[illegible] of Belle Isle westward to the Labrador City area (more than 700 km) and northward to Cape Chidley (more than 800 km). Labrador's size reflects its geological complexity; it encompasses parts of five Canadian Shield structural provinces, within which is found a wide variety of geological environments and more than 3 billion years of geological history. Relatively little mineral exploration has been conducted in Labrador, at least in comparison to the rest of the Canadian Shield, and large tracts remain virtually unexplored. Most of Labrador remains an exploration frontier in every sense of the word.

There is a common perception that Labrador is remote and inaccessible. Although this impression was perhaps true during the heyday of iron-ore exploration and development in the 1950's and 1960's, it is far less true in the 1990's. The main centres of Goose Bay, Labrador City–Wabush, and Churchill Falls are all linked by daily scheduled air service to insular Newfoundland, Quebec and Nova Scotia. Labrador is also connected to the Quebec highway system by a road leading from Baie Comeau to Labrador City (Figure 2). During 1991, the final link will be completed between this road system and the summer-only gravel road that connects Churchill Falls with Goose Bay, thereby completing the road connection between all of the major population centres in Labrador and the Canadian highway system to the south. With the prospect of further hydro development along the Churchill

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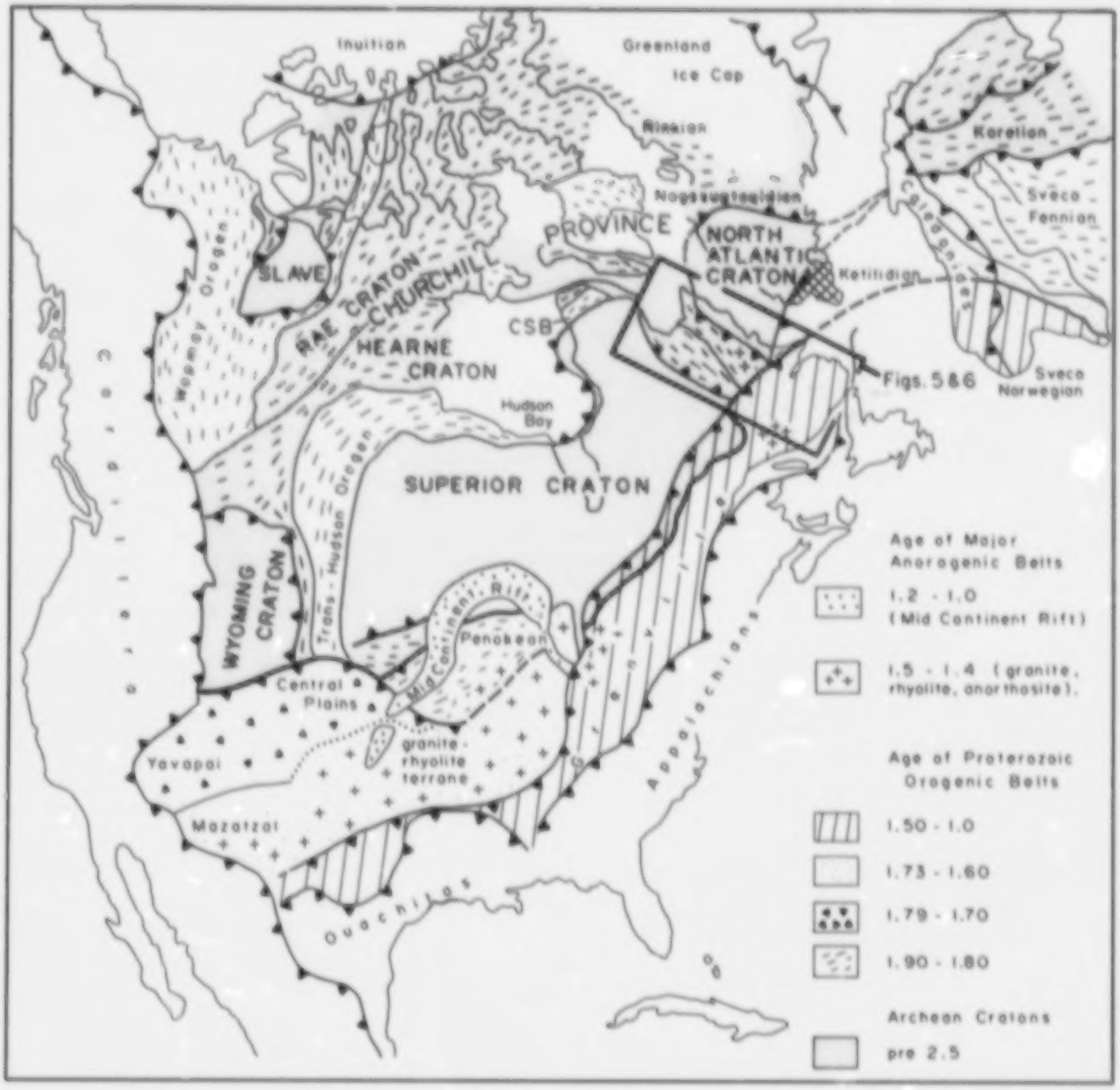

Inuitian
Greenland
Ice Cap
Rinkian
Karelian
Nagssugtoqidian
Caledonides
Sveco Fennian
PROVINCE
NORTH ATLANTIC CRATON
Ketilidian
SLAVE
RAE CRATON
CHURCHILL
HEARNE CRATON
CSB
Figs. 5&6
Sveco Norwegian
Wopmay Orogen
Cordillera
Hudson Bay
Trans-Hudson Orogen
SUPERIOR CRATON
WYOMING CRATON
Mid Continent Rift
Penokean
Central Plains
Grenville
Appalachians
Yavapai
granite-rhyolite terrane
Mazatzal
Ouachitas
Age of Major Anorogenic Belts
1.2 - 1.0 (Mid Continent Rift)
1.5 - 1.4 (granite, rhyolite, anorthosite).
Age of Proterozoic Orogenic Belts
1.50 - 1.0
1.73 - 1.60
1.79 - 1.70
1.90 - 1.80
Archean Cratons
pre 2.5

Figure 1. *Structural provinces of the North America–Greenland–Baltic shields, after Hoffman (1988). Location of Labrador and adjacent areas is shown by box.*

River, the road system will probably be further upgraded in the near future. Western Labrador continues to be served by the Quebec North Shore and Labrador (QNS&L) railway, which offers transport to and from Sept Isles, Quebec. The coastal communities of Labrador, although they remain isolated from the road network, are served by daily scheduled Twin Otter airline service to Goose Bay year-round and by regular coastal-boat (freight and passenger) service from June to November.

Much of interior Labrador is still remote and the only practical means of access is by aircraft. Fixed-wing charter service is available from Goose Bay, Labrador City and Schefferville (Quebec). Helicopters can be chartered in Goose Bay.

As the Newfoundland and Labrador Geological Survey Branch and the Geological Survey of Canada embark upon a new Agreement on Mineral Development at the start of our third decade of concentrated geoscience activities in Labrador in support of mineral development, it is perhaps appropriate to review the significant gains in our understanding of the regional geology and metallogeny of Labrador that this work to date, has brought about. The past 20 years have seen

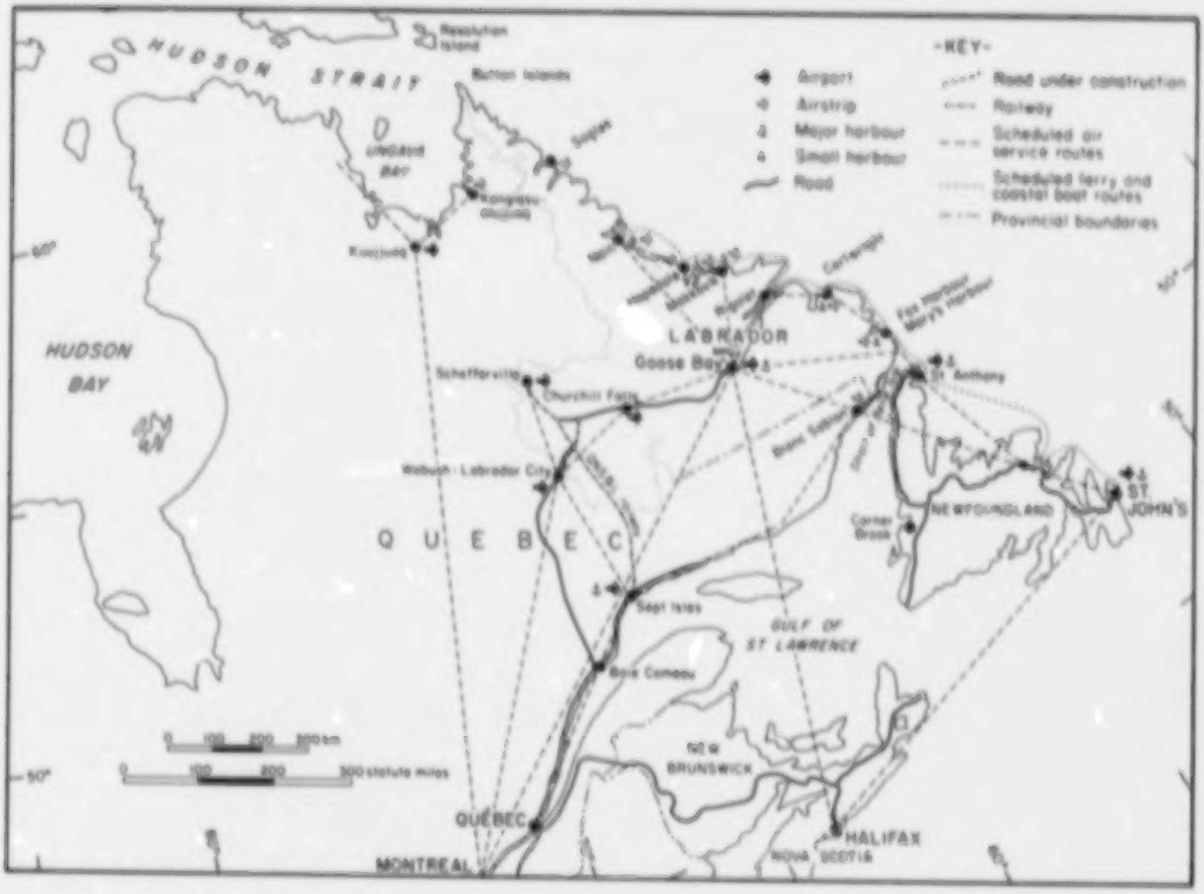

HUDSON STRAIT
Resolution Island
Button Islands
Ungava Bay
Kangiqsualujjuaq
Kuujjuaq
Saglek
Nain
Hopedale
Makkovik
Rigolet
Cartwright
Fox Harbour
Mary's Harbour
LABRADOR
Goose Bay
Schefferville
Churchill Falls
Wabush - Labrador City
Blanc Sablon
St Anthony
HUDSON BAY
QUEBEC
Sept Iles
Baie Comeau
GULF OF ST LAWRENCE
NEWFOUNDLAND
Corner Brook
ST JOHN'S
NEW BRUNSWICK
HALIFAX
NOVA SCOTIA
QUÉBEC
MONTREAL
60°
50°
0 100 200 300 km
0 100 200 300 statute miles
-KEY-
Airport
Airstrip
Major harbour
Small harbour
Road
Road under construction
Railway
Scheduled air service routes
Scheduled ferry and coastal boat routes
Provincial boundaries

Figure 2. *Transport infrastructure of Labrador in the context of eastern Canada.*

significant advances in our understanding of the geology of Labrador, and this has in turn led to substantial changes in our perceptions of the mineral potential of this area. The objectives of this paper are threefold: 1) to point out some of the significant new developments in Labrador geology that might be of particular interest to the mineral-exploration industry; 2) to familiarize the readers with the scope and quality of the geoscientific database that is available for Labrador today; and 3) to suggest some exploration targets in Labrador, the potential of which has not been fully (or in some cases even partially) exploited. This article might be thought of as a road-map for exploration targets in Labrador. Space constraints do not permit all the details to be presented. However, the extensive reference list will lead the interested reader to further details in most areas and any of the authors would welcome personal inquiries on aspects of Labrador geology and mineral potential.

HISTORICAL REVIEW

In March, 1972, the first geological map of Labrador (Greene, 1972) was introduced at the annual meeting of the Prospector's and Developer's Association, compiled mainly from reconnaissance Geological Survey of Canada (GSC) mapping and from detailed exploration-company maps. Although the basic outlines of Labrador geology, including the approximate boundaries and general geology of the Superior, Churchill, Nain, and Grenville structural provinces, were reasonably well established at this time, detailed mapping was sparse and there was relatively little in-depth understanding of the internal geology of the various provinces. Mineral-exploration companies, operating under long-term concession agreements, had provided much of the geological information (a lot of which re-appeared in various Geological Survey of Canada compilations) and almost all of the information on Labrador's mineral resources. At that time, these included the major Fe deposits of the Labrador Trough, showings of Cu and Ni associated with mafic sills in the eastern part of the Trough, and Cu, U, Be and Mo deposits in Proterozoic supracrustal rocks of the Central Mineral Belt (CMB). With the notable exceptions of the western Labrador iron ranges, the Seal Lake Cu province and the U mineralization in the eastern Central Mineral Belt, there were few detailed mineral-deposits studies upon which to base regional metallogenic models, and little basis for suggesting mineral potential in areas where there were no known showings.

The Newfoundland Department of Mines and Energy (NDME) recognized in the early 1970's, that a much improved geoscientific database was essential for promotion of mineral-resource potential in Labrador, particularly in view of the anticipated replacement of the concession system with competitive claim-staking. Geological mapping and detailed study of the mineral deposits, begun in 1973 under the Canada–Newfoundland Mineral Exploration and Evaluation Agreement, was chiefly focussed on areas of demonstrated high-mineral potential in the Central Mineral Belt (Smyth *et al.*, 1974; Marten, 1975; Ryan, 1984) and two years later, programs were initiated in the Labrador Trough (Wardle, 1977). Work was carried out principally by the NDME, but included a significant contribution by geologists of the GSC and by research groups from geology departments of various Canadian universities.

By the early 1980's, mapping of the CMB and the Labrador Trough near the known mineral deposits was complete and genetic models based on detailed studies had been proposed for most deposit types. Mapping projects were expanding outward from these areas, and new projects were underway in the Nain and Churchill provinces in central and northern Labrador and along the northern margin of the Grenville Province. Regional geochemical studies were started in the eastern Grenville Province, Labrador Trough, CMB and parts of the Nain and Churchill provinces under the Canada–Newfoundland Uranium Reconnaissance Program and continued under the subsequent mineral-development agreements. Quaternary studies were initiated in the Melody Lake area in 1981, and industrial mineral-assessment programs began in western Labrador in 1984. Aeromagnetic mapping was begun in the late 1960's.

Now, at the beginning of the 1990's, government-sponsored geoscience programs, funded under four Canada–Newfoundland mineral-development programs, have revolutionized our understanding of the geological history of Labrador and of the exploration potential of the various geological provinces. Regional geological mapping at 1:100,000 scale has been completed over approximately 60 percent of Labrador (Figure 3). There is complete regional geochemical coverage in lake and stream sediments and regional contrasts in geochemical characteristics have been identified that correspond to contrasts in the underlying geology (Figure 4a, b) and re-analysis of archived samples for gold and related elements is underway, scheduled for completion in the early 1990's. Regional aeromagnetic surveys were completed in 1981. Systematic Quaternary mapping has been carried out in areas of high mineral industry interest (e.g., Central Mineral Belt, Strange Lake area, parts of the Labrador Trough) and mineral occurrences in the Central Mineral Belt, western Labrador and the north Labrador coast have been documented for inclusion in the provincial mineral-occurrence data system (MODS) and are or will soon be available as a database for microcomputer. Mineral-occurrence maps have been published or are in preparation for these areas (Figure 3).

The broad framework and many of the details of the geology of the region have now been established, new geological provinces have been recognized and the boundaries of the formerly recognized provinces refined, previously unknown orogenies have been discovered, and significant insights into the accretionary history of the eastern part of the North American Shield have been documented. The present state of knowledge of the geology of Labrador provides a framework for metallogenic interpretation of known mineral deposits and invites speculation concerning the potential of areas where occurrences have not yet been found.

NEW CONCEPTS OF THE GEOLOGY OF LABRADOR

GENERAL GEOLOGY

The general geology of Labrador is shown in Figure 5. Labrador contains parts of five structural provinces (Figure 1) that record a crustal history ranging from about 3.8 to 0.6 Ga. The oldest rocks are preserved in the Archean cratons of the Nain and Superior provinces. These are bounded by the Lower Proterozoic mobile belts of the Churchill and Makkovik provinces. The Grenville Province, which truncates the Churchill and Makkovik provinces in the south, contains vestiges of an Early Proterozoic mobile belt referred to as the Labrador Orogen.

NAIN PROVINCE

The Nain Province is divided broadly into a northern segment, the Saglek block, and a southern segment, the Hopedale block (Figure 6). The Saglek block (cf. Bridgwater *et al.*, 1978) consists predominantly of amphibolite- to granulite-facies granitoid gneiss (3.8 to 2.9 Ga) interspersed with narrow (tens of metres to 2 kilometres) supracrustal belts composed of pelitic–psammitic gneiss and mafic rocks representing mafic metavolcanic rocks and high-level intrusions.

The Hopedale block (cf. Korstgaard and Ermanovics, 1985) consists mainly of a rather similar, although slightly younger (2.9 to 2.3 Ga), granitoid–gneiss dominated terrane with an extensive ~2.8 Ga granitoid intrusive terrane at its southern end (Kanairiktok Intrusive Suite). It also contains two 'greenstone' belts, the relatively low-grade (greenschist) Florence Lake belt and the somewhat higher grade (up to amphibolite) Hunt River belt.

Ages within the Nain Province young to the south, suggesting that the craton has grown by progressive accretion in that direction.

SUPERIOR PROVINCE

The comparatively small part of the western Superior Province present in Labrador is composed of the granulite facies Ashuanipi Complex. As described by Percival (1987), this consists of an older sequence of migmatitic metasedimentary gneisses and lesser metavolcanic mafic rocks, intercalated with broad sheets of migmatitic tonalite

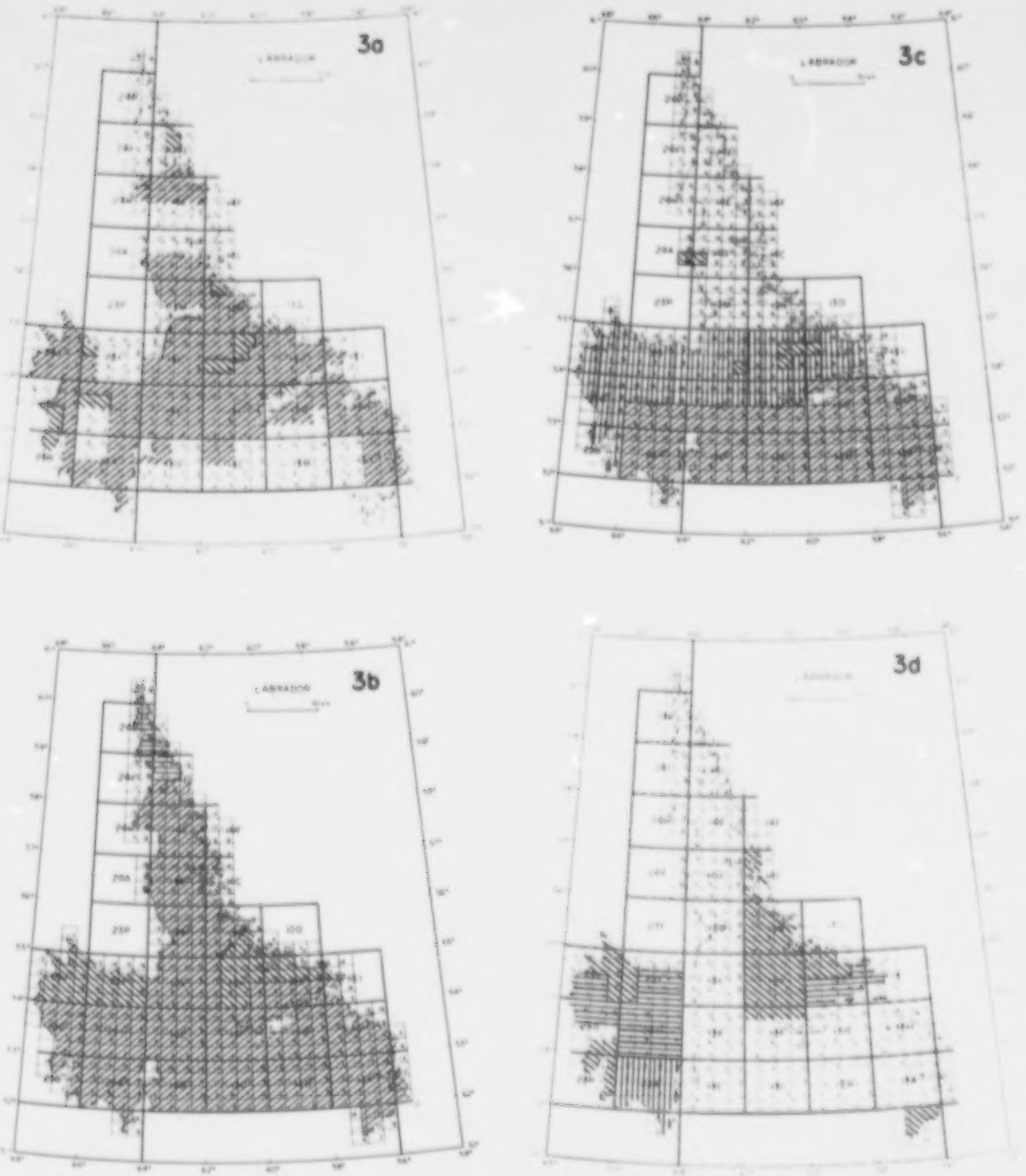


Figure 3. *Maps illustrating the geoscience data coverage for Labrador. a—regional geological mapping. ▨ 1:100,000; ▧ 1:50,000; b—regional geochemical surveys; ▨ lake sediment and water (GSC); ▧ analysis of archived lake-sediment samples for Au and related elements; ≡ stream sediment and water; c—Quaternary mapping; ▧ 1:50,000; |||||| 1:250,000; ▨ 1:500,000; d—Mineral Occurrence Data System; ▧ completed, map published; ≡ data compilation completed, maps to be published; |||||| data compilation in progress.*

gneiss. These are intruded by foliated to massive tonalite and diatexite and by late intrusions of granite and nepheline syenite. U–Pb age determinations indicate crust formation between approximately 2.78 and 2.64 Ga and suggest that the Ashuanipi Complex is a high-grade equivalent of the Quetico Subprovince of the western Superior Province (Mortenson and Percival, 1987).

CHURCHILL PROVINCE

The Churchill Province is now recognized to have a well-defined tripartite subdivision (Wardle *et al.*, *in press*,b) (Figure 6). The western part of the province consists of a west-verging fold and thrust belt formed by low-grade sedimentary and volcanic rocks of the Labrador Trough. This has been more recently referred to as the 'New Quebec Orogen' (Hoffman, 1988). The central Churchill Province is rather poorly known but appears to consist predominantly of reworked Archean rocks of the Rae Province (Hoffman, 1988), structurally juxtaposed with the Labrador Trough along mylonitic shear zones. The Rae Province rocks are intruded by the axial De Pas batholith. Recognizable Archean rocks include anorthosites and related gabbroic rocks, and a 'greenstone'-type belt near the eastern end of the Smallwood Reservoir area.

The eastern part of the Rae Province is structurally juxtaposed against reworked rocks of the Nain Province in the Torngat Orogen. The site of the suture is the Abloviak shear zone, a major sinistral shear located within a linear belt of mylonitized paragneiss (Tasiuyak gneiss). To the east of the Abloviak shear zone, the reworked Archean gneisses of the Nain Province and Lower Proterozoic Ramah Group cover rocks, define an east-verging fold-and-thrust belt. Lower Proterozoic orogenesis in the Churchill Province was largely transpressional involving oblique convergence of the Superior and Nain cratons on the Rae Province (see van Kranendonk, 1990; Wardle *et al.*, *in press*,a and references therein).

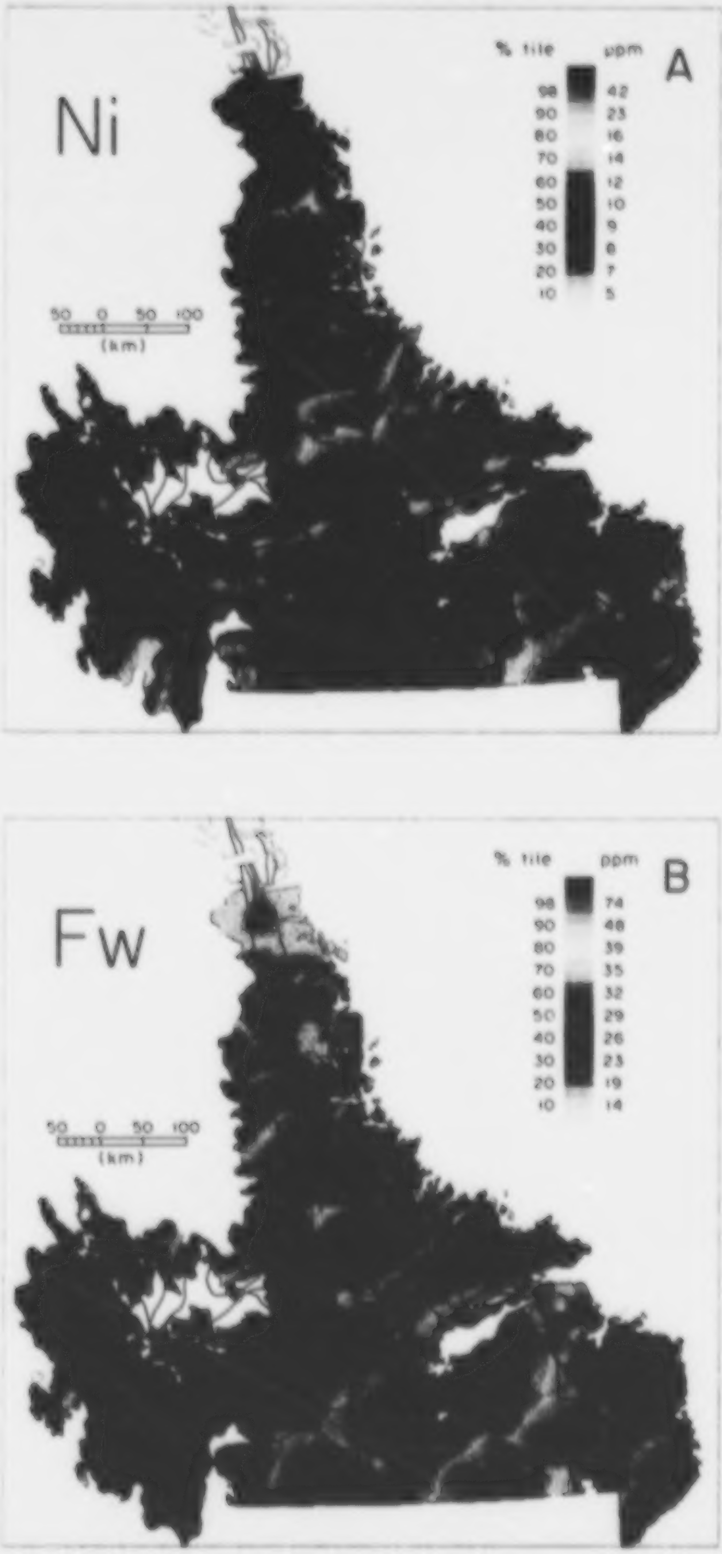


Figure 4. *Representative regional geochemical maps for Labrador. A–Ni in lake sediments; B–fluorine in lake waters. Geological boundaries as in Figure 5.*

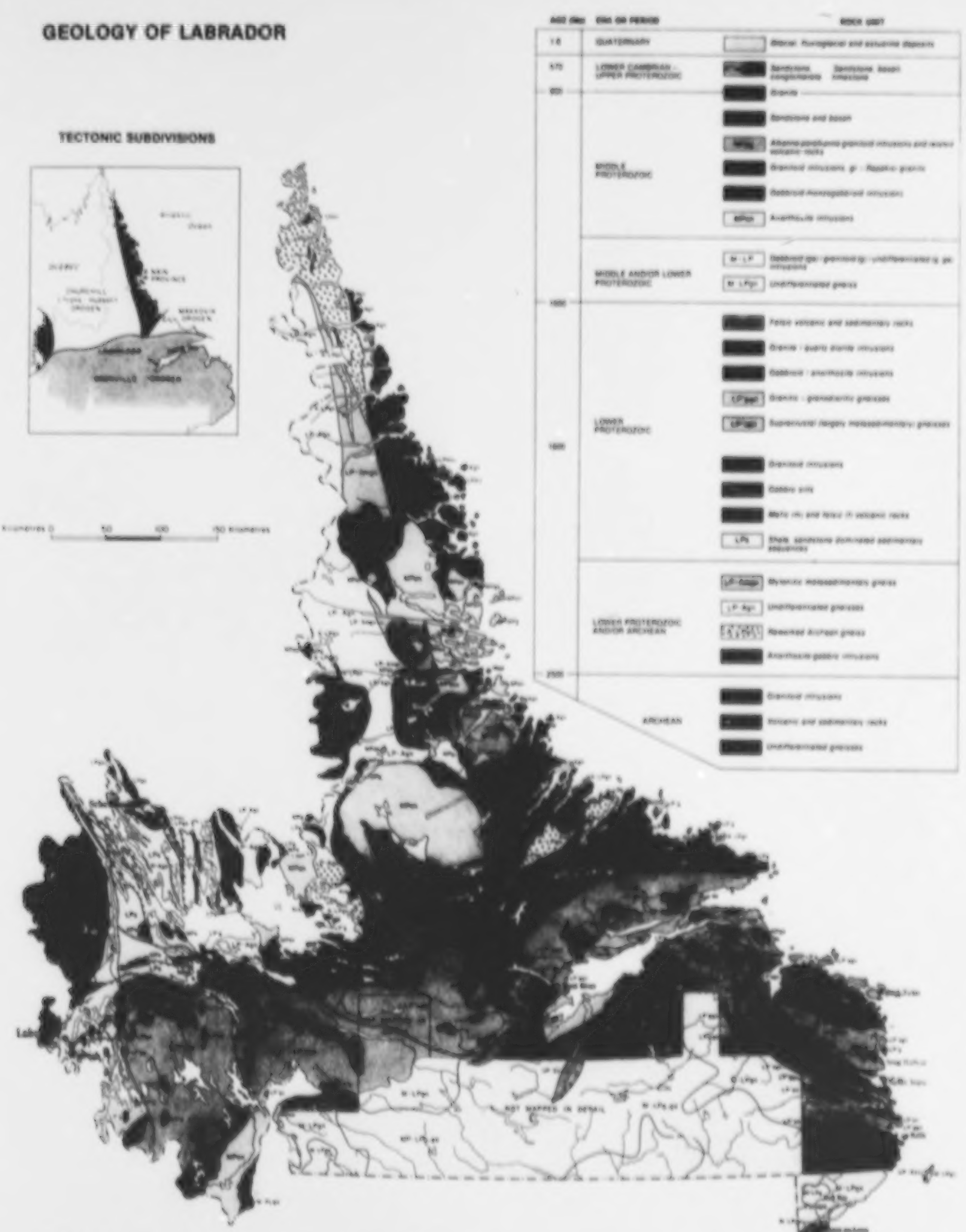

GEOLOGY OF LABRADOR
TECTONIC SUBDIVISIONS
Atlantic Ocean
NAIN PROVINCE
CHURCHILL PROVINCE
MAKKOVIK OROGEN
GRENVILLE OROGEN
Kilometres 0 50 100 150 Kilometres
NOT MAPPED IN DETAIL
AGE (Ma)
ERA OR PERIOD
ROCK UNIT
1.6
QUATERNARY
Glacial, fluvioglacial and estuarine deposits
570
LOWER CAMBRIAN - UPPER PROTEROZOIC
Sandstone, conglomerate
Sandstone, basalt intrusions
900
Granite
MIDDLE PROTEROZOIC
Sandstone and basalt
Alkaline-peralkaline granitoid intrusions and related volcanic rocks
Granitoid intrusions, gr - Rapakivi granite
Gabbroid-monzogabbroid intrusions
MPan
Anorthosite intrusions
MIDDLE AND/OR LOWER PROTEROZOIC
M-LP
Gabbroid (gb), granitoid (g), undifferentiated (g, gb) intrusions
M-LPgn
Undifferentiated gneiss
1600
LOWER PROTEROZOIC
Felsic volcanic and sedimentary rocks
Granite - quartz diorite intrusions
Gabbroid - anorthosite intrusions
LPgn
Granitic - granodioritic gneisses
LPgn
Supracrustal (largely metasedimentary) gneisses
1800
Granitoid intrusions
Gabbro sills
Mafic (m) and felsic (f) volcanic rocks
LPs
Shale, sandstone dominated sedimentary sequences
LOWER PROTEROZOIC AND/OR ARCHEAN
LP-Amgn
Mylonitic metasedimentary gneiss
LP-Agn
Undifferentiated gneisses
Reworked Archean gneiss
Anorthosite-gabbro intrusions
2500
ARCHEAN
Granitoid intrusions
Volcanic and sedimentary rocks
Undifferentiated gneisses

Figure 5. *Simplified geological map of Labrador (geology current to 1987). Units are represented in terms of rock type and age, rather than stratigraphic nomenclature. Names of major rock units referred to in the text are depicted in Figure 6.*

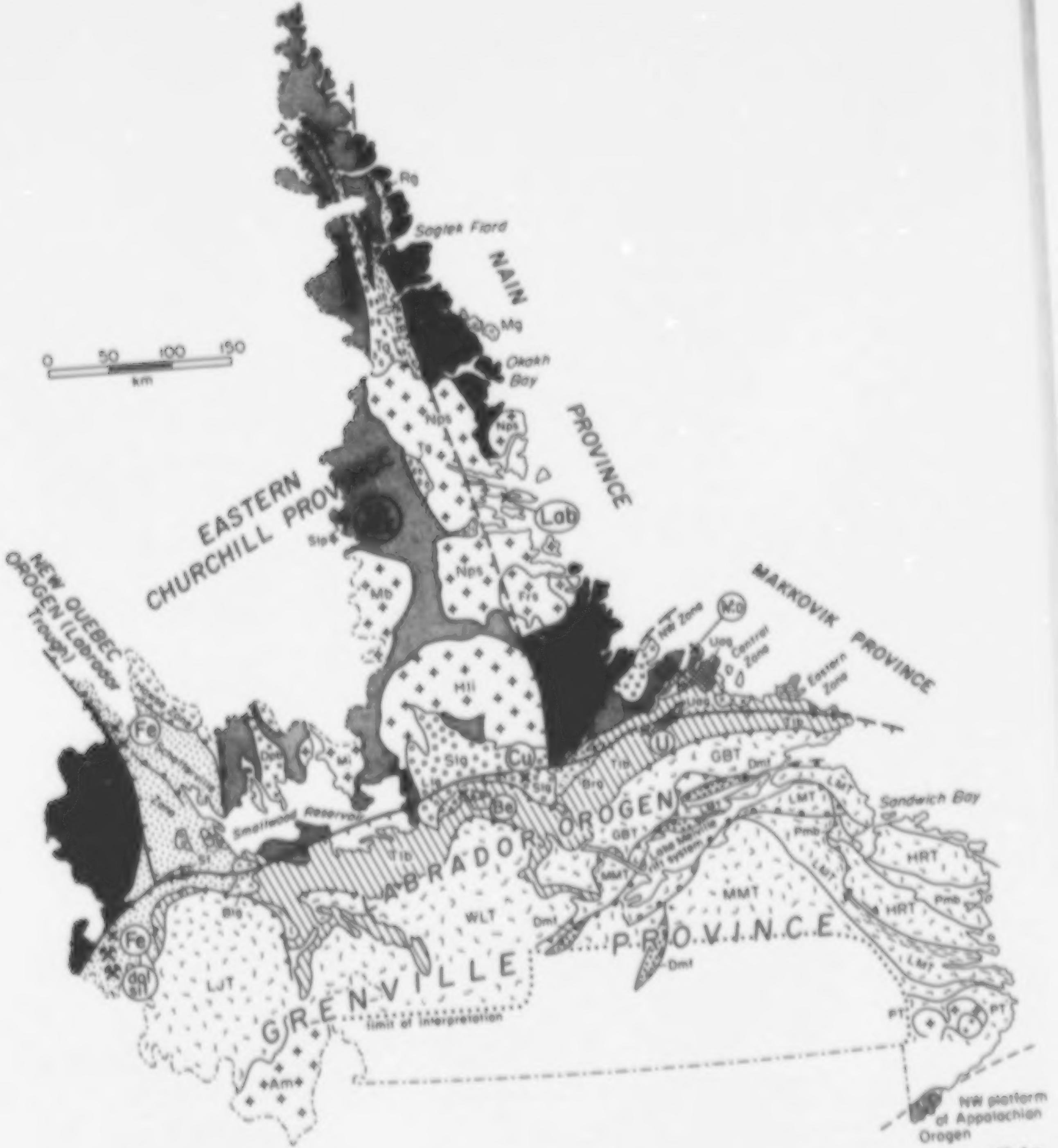

0 50 100 150
km
TORNGAT
Rg
Saglek Fiord
NAIN
Mg
Okak Bay
Nps
Tg
PROVINCE
EASTERN
CHURCHILL PROVINCE
Lab
Slp
Mb
Fls
NEW QUEBEC OROGEN (Labrador Trough)
Hli
MAKKOVIK PROVINCE
NW Zone
Mo
Uag
Central Zone
Eastern Zone
Fe
Dmf
Mi
Slg
Cu
U
Be
Smallwood Reservoir
Sf
Tlb
Brg
GBT
Dmf
LABRADOR OROGEN
LMT
Sandwich Bay
Lake Melville rift system
MMT
Pmb
HRT
Blg
WLT
PROVINCE
GRENVILLE
LJT
dol sil
limit of interpretation
Am
PT
NW platform of Appalachian Orogen

Figure 6. *Major stratigraphic and tectonic elements of Labrador, also showing producing mines and major mineral deposits: Tectonic Features: LJT—Lac Joseph terrane; WLT—Wilson Lake terrane; MMT—Mealy Mountains terrane; GBT—Groswater Bay terrane; LMT—Lake Melville terrane; HRT—Hawke River terrane; PT—Pinware terrane; ABZ—Abloviak shear zone. Stratigraphic Units: Am—Atikonak massif; Dmf—Double Mer Formation; Pmb—Paradise metasedimentary belt; Tlb—Trans-Labrador Batholith; Sf—Sims Formation; Slg—Seal Lake Group; Blg—Blueberry Lake Group; Llg—Letitia Lake Group; Brg—Bruce River Group; Mlg—Moran Lake Group; Lag—Lower Aillik Group; Uag—Upper Aillik Group; Flb—Florence Lake belt; Hrb—Hunt River belt; Nps—Nain Plutonic Suite; Hli—Harp Lake Intrusion; Mi—Michikamau Intrusion; Mb—Mistastin batholith; Slp—Strange Lake pluton; Mg—Mugford Group; Rg—Ramah Group; Tg—Tasiuyak gneiss; Frs—Flowers River suite.*

Legend for Figure 6

Paleozoic

▩ *Cambro-Ordovician rocks of NW platform to Appalachian Orogen*

Upper Proterozoic (1.0 – 0.57 Ga)

▨ *Late Precambrian – Early Paleozoic rocks of Lake Melville rift system*
□ *Undifferentiated rocks of Grenville Province*
▨ *Post-Grenville granites (ca. 0.97 – 0.95 Ga)*

Middle Proterozoic (1.6 – 1.0 Ga)

▨ / ▨ / ▨ *Middle Proterozoic plutonic / sedimentary / volcanic rocks*

Lower Proterozoic (2.1 – 1.6 Ga)

▨ *Late Lower Proterozoic (ca. 1.65 Ga) volcanic rocks*
▨ *Late Lower Proterozoic plutonic rocks (ca. 1.65 Ga – only the Trans-Labrador batholith is shown)*
▨ *Undifferentiated gneissic and plutonic rocks of Labradorian (1.7 – 1.6 Ga) age, overprinted by Grenvillian deformation*
▨ / ▨ / ■ *Early Lower Proterozoic (2.1 – 1.8 Ga) sedimentary / mafic volcanic / felsic volcanic rocks*
▨ *Plutonic rocks*
▨ *Tasiuyak paragneiss*
▤ *Juvenile(?) gneiss of Makkovik Province*
■ *Gneissic rocks (largely reworked Archean) of Eastern Churchill and Makkovik provinces*

Archean (>2.5 Ga)

■ *Undifferentiated gneiss of Nain and Superior provinces*
□ *Archean metavolcanic belts*

Symbols

Structural province boundaries
Thrust faults
Ductile shear zones
Normal fault

Mineral deposits

× *Major mineral deposit*
⚒ *Producing mine*

Fe – Iron
Cu – Copper
Y – Yttrium
Zr – Zirconium
Be – Beryllium
REE – Rare earth elements
U – Uranium
M – Molybdenum
Lab – Labradorite
Dol – Dolomite
SiO_2 – Silica

MAKKOVIK PROVINCE

This triangular crustal segment is the western continuation of the more extensive Ketilidian Mobile Belt of southern Greenland (Sutton *et al.*, 1972) and can be divided into three discrete zones (Gower and Ryan, 1986; Figure 6).

The northern zone consists mainly of reworked Archean granitoid gneisses equivalent to those in the southern Nain province, infolded with Proterozoic supracrustal rocks that are probably equivalent to the Moran Lake and Lower Aillik groups.

A narrow central zone includes the relatively well-preserved supracrustal rocks of the pre-1.86 Ga Moran Lake and Lower Aillik groups, comprising clastic sedimentary rocks overlain by thick submarine basalt sequences. Both groups are disposed in northwest-verging fold-and-thrust belts; the Lower Aillik Group is structurally overlain by the more extensive 1.86 to 1.81 Ga Upper Aillik Group, which is dominantly composed of felsic volcanic and pyroclastic rocks.

The eastern zone of the Makkovik Province is a complex, polyphase, syn- to posttectonic granitoid batholith, including suites of ca. 1.8, 1.72 and 1.65 Ga (Kerr, 1989; Kerr and Krogh, 1990) and containing small supracrustal and gneissic remnants. Although compositionally varied, the two older suites are dominated by potassic, high-silica granites; similar rocks intrude the Upper Aillik Group and gneisses of the central and northern zones respectively. This pre-1.65 Ga magmatism in the Makkovik Province has geochemical affinities to post-orogenic and anorogenic environments, whereas the 1.65 Ga magmatism is probably related to the Labradorian Orogeny.

Neodymium isotopic evidence indicates that the northern and central zones of the Makkovik Province are underlain by Archean basement, whereas the eastern zone shows no evidence of a significantly older basement complex (Kerr and Fryer, *in press*). It is likely that a substantial part of the gneisses and supracrustal rocks in the eastern part of the Makkovik Province comprises accreted juvenile crust.

GRENVILLE PROVINCE

The northern margin of the Grenville Province contains a belt of high-grade metamorphic and associated plutonic rocks (ca. 1.71 to 1.62 Ga) referred to as the Labrador Orogen (Figure 6) (Nunn *et al.*, 1985). The northern margin of this belt is marked by a curvilinear belt of granitoid rocks termed the Trans-Labrador batholith (TLB) and thought to be about 1.65 Ga old. At its eastern end, the 1.65 Ga TLB is only part of a composite granitic terrane that also includes ca. 1.80 and 1.72 Ga granitic suites (see above). The Labrador Orogen south of the TLB consists of tonalitic–granodioritic orthogneiss, pelitic paragneiss, numerous metagabbroic units (of which the anorthosite of the Mealy Mountains terrane is the largest and best preserved example) and voluminous granitoid plutonic rocks that range in age from 1.71 to 1.62 Ga.

The southward extent of the Labradorian rocks has yet to be fully established. Analogies with the western Grenville Province and the Baltic Shield suggest that Middle Proterozoic rocks should become more prevalent to the southeast (Gower and Owen, 1984; Gower and Ryan, 1986). Preliminary work on the southeast Labrador coast (Gower *et al.*, 1988; Tucker and Gower, 1990) has revealed the existence of middle Proterozoic granites in the Pinware Terrane and tends to confirm this suggestion. Syn- to post-Grenvillian granites also become increasingly prevalent to the south and form a major addition to the crust of the southern Grenville Province.

The Grenvillian Orogeny (ca. 1.0 Ga) resulted in regional high-grade metamorphism and north-directed thrusting, apparently in response to continental collision from the south. The zone within 100 km of the Grenville Front was subject to massive thrusting, local crustal imbrication and widespread ductile shearing. Large areas of the interior Grenville Province, however, escaped significant Grenvillian reworking and retain their generally Labradorian character.

MIDDLE PROTEROZOIC PLUTONISM AND SEDIMENTATION

Large areas of northern and central Labrador were subject to extensional tectonism in the period 1.45 to 1.1 Ga. The most obvious manifestations of this event are massif-type anorthosite–granite complexes and related gabbroic intrusions formed between 1.45 and 1.2 Ga. The largest and best examples were intruded within the Grenville Province and along the Nain–Churchill Province boundary zone and overlapped with a more limited period of dyke intrusion, and localized peralkaline–alkaline magmatism in the period 1.3 to 1.1 Ga (Hill and Miller, *in press*). The latter part of this period was marked by intrusion of the Strange Lake and Flowers River peralkaline centres, an igneous event that is probably equivalent to late alkaline magmatism of the Gardar Province in Greenland.

Middle Proterozoic sedimentation is represented by the Sims Formation (arkose, quartzite) of western Labrador and the Seal Lake Group (terrestrial arkose, quartzite, shale, basalt flows and gabbro sills) of central Labrador (Figure 6). The two groups were deposited in shallow-marine to terrestrial conditions but are not necessarily temporal equivalents. Both units span the Grenville–Churchill Province boundary and have been affected by Grenvillian deformation.

LATE PROTEROZOIC PLUTONISM AND SEDIMENTATION

Arkoses and conglomerates of the Double Mer Formation (late Precambrian to early Paleozoic) are preserved in a series of half-grabens, which form part of the Lake Melville rift system in eastern Labrador (Gower *et al.*, 1986a). A smaller, subparallel rift system has also been discovered in the Sandwich Bay area. Subparallel mafic dykes of ca. 0.615 Ga age (Kamo *et al.*, 1989) provide the best indication of the time of rift development and indicate a temporal link with initial rifting in the St. Lawrence rift system (northwestern margin of the Appalachian Orogen) to the south. Thin lamprophyre dykes of ca. 0.57 Ga in the Makkovik Province may be similarly related.

PHANEROZOIC

Cambro-Ordovician siliciclastic rocks, basalt flows and limestone of the Labrador Group are exposed on the southeast coast of Labrador, where they form part of the western platform to the Appalachian Orogen.

Younger rocks are volumetrically insignificant in Labrador. Various mafic dykes ranging in age from Carboniferous to Cretaceous are known from the coastal region and some of the Jurassic–Cretaceous examples have a kimberlitic affinity (Foley, 1989). Cretaceous gravels and lateritic deposits occur within a small graben in the Proterozoic iron deposits of western Labrador, and record a period of intense tropical weathering that led to the economically important secondary enrichment of the Schefferville iron deposits, and to the formation of leached silica deposits in the Labrador City area.

CORRELATIONS THROUGHOUT THE NORTH AMERICAN AND BALTIC SHIELDS

Broad correlations of the geology of Labrador with other parts of the North American Shield and with Greenland and Scandinavia (Figure 1) have been known for some time (Wynne-Edwards and Hasan, 1970; Sutton *et al.*, 1972; Bridgwater *et al.*, 1973; Gower and Owen, 1984; Gower *et al.*, *in press*,x). These correlations are of considerable economic significance, as they allow an evaluation of the mineral potential of areas in Labrador by analogy with other areas, where the metallogenic relationships are better documented and understood. They also allow us to use the presence of specific deposit types in geological terranes such as Scandinavia, Greenland, and other parts of Canada to predict mineral-exploration potential in correlative terranes in Labrador.

The Nain Province is part of the fragmented North Atlantic Craton, the greater part of which is now exposed in Greenland and northwest Scotland.

The part of the eastern Churchill Province exposed in Labrador forms a southern arm of the trans-Arctic portion of the Churchill Province. Rocks in the western part of this belt, referred to as the Labrador Trough (or 'New Quebec Orogen'; Hoffman, 1988) are correlative with the Cape Smith foldbelt and other rocks along the eastern side of Hudson Bay that form part of the 'Circum Ungava Belt' (Dimroth *et al.*, 1970). The central part of the eastern Churchill Province has been correlated with the Archean Rae Province (Hoffman, 1988), which forms a major interior part of the trans-Arctic Churchill Province. The eastern part of the eastern Churchill Province (Torngat Orogen) is inferred to extend through the southern tip of Baffin Island (Hoffman, 1989) and into the Nagssugtoqidian mobile belt of western Greenland (Korstgaard *et al.*, 1987).

The Makkovik Province of Labrador has long been recognized as the western extension of the Ketilidian mobile belt of southern Greenland (Sutton *et al.*, 1972; Gower and Ryan, 1986) which, in turn, is probably correlative with the Svecofennian belt of the Baltic Shield.

The Grenville Province in Labrador includes the ca. 1.65 Ga Labrador Orogen, which has correlatives in the Sveconorwegian Province of southern Scandinavia (Gaal and Gorbatschev, 1987) and the Mazatzal Orogen of the southwestern United States (van Schmus and Bickford, 1981; Hoffman, 1989). The exposed Grenville Province extends from southwestern Ontario and upstate New York to Labrador, and can be traced eastward into the Sveconorwegian Province of Scandinavia. A largely buried extension of the Grenville Province extends southward from Ontario as far as Texas and Mexico (Hoffman, 1989).

MINERAL ENVIRONMENTS OF LABRADOR

The increased geological understanding outlined above has spawned a new generation of metallogenic ideas and interpretations in Labrador. Coupled with data from mineral deposit, regional geochemical and Quaternary studies, our understanding of the genesis of known mineral deposits in Labrador has been improved, and new targets for future resource development have been identified.

In this section, we outline opportunities for mineral-resource development in Labrador that have been highlighted or identified during the past 15 years of geoscience activities. To this end, we have chosen to focus on exploration ideas and models that are relatively new. For example, geological descriptions and metallogenic models for the Fe deposits of the Labrador Trough (Stubbins *et al.*, 1961; Gross, 1968; Zajac, 1974), Cu deposits of the Seal Lake area (Evans, 1952; Brummer and Mann, 1961; Gandhi and Brown, 1975; Ryan, 1984; Wilton, 1989a), and U deposits of the Central Mineral Belt (Beavan, 1958; Bailey, 1979; Gandhi, 1976; Gower *et al.*, 1982; Ryan, 1984; White and Martin, 1980; Wilton and Wardle, 1987) have been extensively documented in the literature and are accordingly not treated further. Producing mines and major mineral deposits of Labrador are shown on Figure 6.

This paper is not intended to present a lengthy discussion of the geological data and genetic arguments for the exploration targets and models we propose. Rather, it is meant to provide an up-to-date review of the potential of Labrador as a focus for exploration. To do this, we take a three-pronged approach to: i) provide a perspective on new metallogenic ideas that have been generated during 15 years of geoscientific research in Labrador; ii) set forth some ideas for grassroots exploration that may warrant follow-up; and, iii) cite appropriate literature references by which the reader can start to acquire the additional information needed to transform an idea into an exploration target.

BASE AND PRECIOUS METALS IN ARCHEAN GREENSTONE BELTS

Introduction

The mineral potential of large parts of the Canadian shield west of Labrador, and indeed of Archean cratons worldwide, is closely tied to the occurrence of Archean greenstone belts, particularly because of their endowment of volcanogenic polymetallic and mesothermal precious-metal deposits. In Labrador, rocks of the Nain and Churchill provinces contain both low-grade greenstone belts, and their high-grade equivalents, which may be prospective for these and other deposit types (Figure 7). High-grade supracrustal sequences in the northern Nain and Churchill provinces may be remnants of greenstone belts, with the attendant possibility that sulphide orebodies may have been preserved, albeit at high metamorphic grade.

Nain Province

The two best known Archean 'greenstone' belts in Labrador are the Florence Lake and Hunt River belts in the Hopedale Block, southern Nain Province (Figure 8). The generally greenschist-facies Florence Lake belt is a true greenstone belt. The Hunt River belt is locally metamorphosed to upper-amphibolite grade but is geologically similar to the Florence Lake belt; it is herein treated, for convenience, as a greenstone belt as well. Both trend approximately northeast, extend for several tens of kilometres along strike, and are intruded by the Kanairiktok Intrusive Suite, a typical Archean tonalite–trondhjemite–granodiorite association.

The Florence Lake belt consists mainly of mafic flows and pillow lavas, mafic subvolcanic intrusive rocks, and minor felsic metavolcanic and metasedimentary rocks, generally at greenschist to amphibolite facies (Ermanovics and Korstgaard, 1981; Ermanovics *et al.*, 1982; Brace and Wilton, 1990; Brace, 1991). The Hunt River belt is not as well known, but appears to contain a higher proportion of mafic intrusive rocks and is preserved in the amphibolite facies (Jesseau, 1976; Collerson *et al.*, 1976). Concordant lenses of ultramafic rocks are widespread in both belts and are interpreted as early intrusions related to the greenstone belt magmatism. The Hopedale Block generally has only a thin cover of till and geochemical exploration methods using soil or till should be effective exploration techniques over both of these 'greenstone' belts.

There are a number of pyritic–pyrrhotitic Cu–Ni prospects in the Florence Lake and Hunt River belts (Figure 8). The best known of these is the Baikie Prospect in the Florence Lake belt, comprising locally massive pentlandite, pyrrhotite, pyrite, minor chalcopyrite and magnetite associated with meta-ultramafic and actinolite schist enclaves in the Kanairiktok Intrusive Suite. The sulphides are enriched in PGE and normalized PGE profiles are similar to those for Archean, komatiite-related mineralization (Brace and Wilton, 1990). Several other small prospects within both the Florence Lake and Hunt River belts contain Cu and Ni, while others are dominantly pyritic, and there is a regional Ni lake-sediment anomaly over the southern part of the Florence Lake Belt (Hornbrook and Friske, 1988a). Brace (1991) has suggested that taken as a whole, these prospects may suggest a potential for further komatiite-related Cu–Ni mineralization.

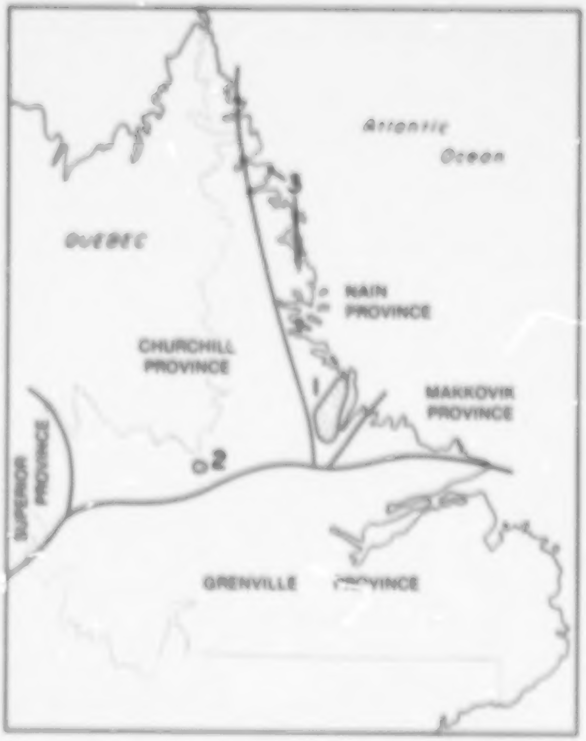


Figure 7. *Target areas for base and precious metals hosted by Archean supracrustal (greenstone) sequences. 1–Hopedale Block, southern Nain Province; 2–Petscapiskau Group, southern Churchill Province; 3–high-grade supracrustal rocks, Saglek Block, northern Nain Province.*

Although it seems likely that deposition models appropriate to the Baikie prospects can be widely applied within these belts, it is not clear whether all known sulphide occurrences are part of a Cu–Ni–ultramafic assemblage. Felsic volcanic rocks occur locally and, by analogy with classic greenstone belts, may indicate that environments favourable for volcanogenic massive sulphide (VMS) deposition are also present. Minor sulphide mineralization is known to be spatially associated with felsic volcanics in the Florence Lake belt (particularly in the Adlatok Bay–Ujoktok Bay area). In this context, Brace (1991) has described some small Cu–Zn sulphide occurrences associated with ankeritic sedimentary (exhalative) rocks.

Finally, deformation in these greenstone belts is locally accompanied by carbonitization and quartz veining, and environments favourable for mesothermal gold deposits might

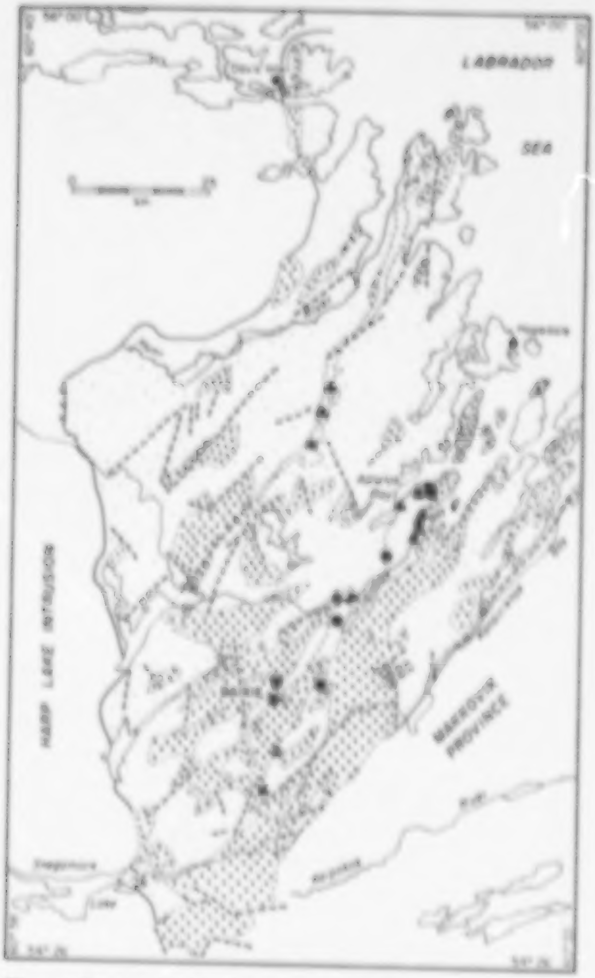


Figure 8. *General geology of the Hopedale Block. Light stipple—undifferentiated gneiss; heavy stipple—greenstone-belts, Hunt River belt in the north, Florence Lake belt in the south; x—intrusive rocks; symbols indicate known showings; squares—Cu-Ni; circles—Cu; triangles—Py.*

well exist. Regional lake-sediment surveys indicate locally elevated Au values over the Hunt River belt, Sb values over the Florence Lake belt, and As over both belts (Hornbrook and Friske, 1988a). However, investigations to date indicate that most deformation-related veins are relatively deficient in sulphides (Brace, 1991), and none has demonstrated precious-metal enrichments.

The Archean gneiss complex of northern Labrador includes numerous belts of amphibolite- to granulite-facies supracrustal rocks, among which are banded iron formation and banded metavolcanic rocks. Equivalent rocks in Greenland host widespread Cu and W showings, to the extent that the west coast of Greenland is cited as a tungsten province (Apell, 1988). The W was deposited in at least two mineralizing events, one of which is interpreted to be submarine exhalative in origin. In addition to anomalous Cu and W, some of the supracrustal rocks in Greenland are enriched in Sn and Zn. By analogy with northern Greenland, the northern part of the Nain Province might potentially contain similar mineralized environments. Lake sediments in this area contain generally high Ni and Cu and are locally high in Pb, As, Ag, Mo, U and Zn, especially over amphibolite-grade rocks south of Saglek Fiord (Hornbrook and Friske, 1988a).

Churchill Province

Recent U–Pb dating in western Labrador has suggested that volcanic and related rocks previously assigned to the Petscapiskau Group in the southern part of the Churchill Province (Emslie, 1970; Nunn and Noel, 1982; Figure 7) form part of an Archean greenstone belt (Nunn *et al.*, *in press*). The Archean rocks outcrop at the southeastern end of the Smallwood Reservoir and comprise a greenschist- to amphibolite-facies assemblage of dominantly mafic volcanic rocks, associated intrusive rocks and volcaniclastic sedimentary rocks. Rhyolite clasts in conglomerates indicate that there may have been coeval felsic volcanism. The area has received little exploration to date and there are no known showings. It may present a good grassroots target for volcanogenic massive sulphides and gold.

The northern part of the Churchill Province contains several belts of supracrustal gneisses. Rusty, sulphide-bearing zones are locally present, but none has been thoroughly examined, and the nature of the mineralization has not been documented. Reconnaissance sampling of several of these zones in 1987 did not produce any significant base- or precious-metal anomalies (A.B.R., unpublished data); however, more detailed work is warranted.

GOLD

Introduction

Although there are not many known gold occurrences in Labrador, there are several environments in which there appears to be a significant exploration potential (Figure 9). Minor gold occurrences are known from a variety of settings ranging from Archean high-grade terranes to Proterozoic supracrustals.

Eastern Superior High-Grade Terranes

The Ashuanipi Complex, western Labrador, comprises high-grade metamorphic rocks that constitute the eastern edge of the Superior Province. Interest in gold in this area was sparked by the report of a new gold discovery in adjacent Quebec (Lapointe, 1986) and by anomalous concentrations of gold pathfinder elements in regional lake-sediment data (Geological Survey of Canada, 1982a,b) in the mid-80's. During 1986, reconnaissance geological and regional geochemical studies carried out by the Newfoundland Department of Mines and Energy (Thomas and Butler, 1987;

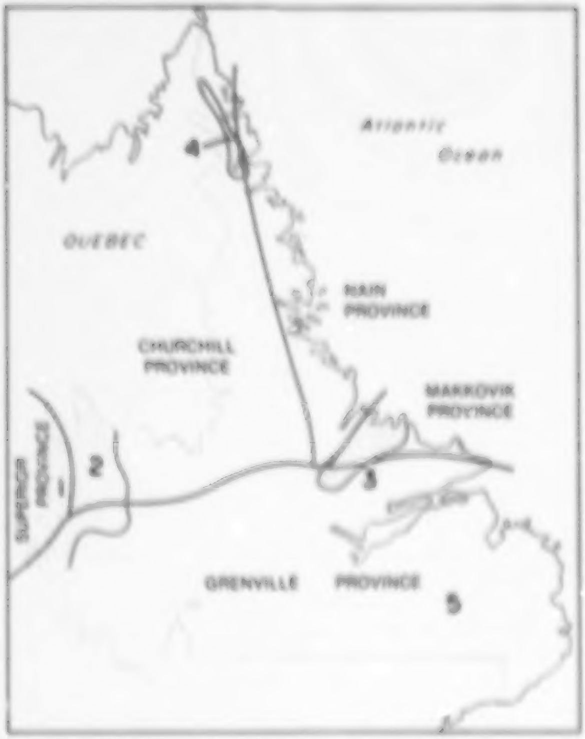


Figure 9. *Target areas for gold exploration. 1–High-grade terranes of the Ashuanipi Complex, eastern Superior Province; 2–Labrador Trough fault zones; 3–Central Mineral Belt (Moran unconformity, eastern Makkovik Province lodes, Bruce River Group); 4–north Labrador shear zones; 5–southern Grenville.*

Butler, 1987; McConnell and Newman, 1988) showed that anomalous concentrations of gold were also present in lake sediments and locally in bedrock, and this sparked considerable claim staking in the area.

More recently, the Geological Survey of Canada has re-analysed archived regional lake-sediment samples from the northern Ashuanipi Complex for gold and related elements (Hornbrook and Friske, 1989). These analyses have identified new areas of anomalous gold enrichment (Figure 10a) and indicate the coincidence of gold, arsenic, tungsten enrichments. Geochemical surveys using soil or till should provide an effective exploration approach in this area, because of the generally thin drift cover (McConnell and Newman, 1988).

Many of the gold deposits in Quebec, which have been drilled by Mazarin Inc., are spatially associated with magnetite iron formation in high-grade Archean supracrustal sequences. A possible deposit model might involve dilatancy in the iron formation during deformation resulting from competency contrast with the surrounding rocks, which would focus the metal-bearing fluids, with the iron acting as a chemical trap for gold. Gold showings in the equivalent rocks in Labrador are associated with pyritiferous zones and locally with mafic (amphibolitic) units. Whether these are sedimentary units or whether they contain iron formation has not been established.

Although Au mineralization is not widely known from high-grade terranes in Canada, significant deposits associated with meta-iron formations are currently being worked in similar Archean granulite-facies rocks in southern Zimbabwe (Böhmke and Varndell, 1986) and may provide an exploration model for gold in the Ashuanipi Complex.

Labrador Trough Thrust Faults

Recent results from the re-analysis of lake-sediment samples from western Labrador show elevated Au–As values over parts of the Labrador Trough (Hornbrook and Friske, 1989; Figure 10a); the highest concentrations are associated with the eastern margin of the Trough. Although the Au anomaly is too broad to allow definitive correlation with any single structure, the possible association with major thrust faults in this area is noteworthy. Mesothermal gold mineralization is commonly sited in second- and third-order structures related to major, trans-crustal faults (e.g., Eisenlohr *et al.*, 1989; Kerrich, 1989; Barley and Groves, 1990). An analogy for the Labrador Trough lake-sediment anomalies may be provided by east-central Newfoundland, where new gold discoveries are associated with Sb and As lake-sediment anomalies of regional extent. These anomalies apparently reflect large-scale movement of Au and related elements (Davenport and Nolan, 1989) and have locally resulted in ore-grade concentrations of Au and Sb (Tallman, 1990; Evans, *this volume*). Gold anomalies in the Labrador Trough may reveal a similar potential.

Kanairiktok Unconformity

Along the northern edge of the Central Mineral Belt, the basal Lower Proterozoic supracrustal rocks, clastic sedimentary and mafic volcanic rocks assigned to the Moran Lake Group, unconformably overlie foliated granite and tonalite assigned to the ca. 2.8 Ga Archean Kanairiktok Intrusive Suite. Carbonate–sericite alteration in the basement, immediately below the unconformity, is locally developed regionally along the strike extent of the Moran Lake Group (approximately 85 km), and is generally interpreted to reflect Lower Proterozoic weathering (Ryan, 1984).

There are a number of epigenetic galena and sphalerite bearing quartz–carbonate (± barite) veins both within the supracrustal shales and in the paleoweathered surface of the underlying basement, which appear to be spatially related to this unconformity (Figure 11). These include the Ellingwood, Green Pond and Kanairiktok #14 prospects (Ryan, 1984; Wilton *et al.*, 1987). At the Kanairiktok #14 prospect, the mineralization is in the basement, and is associated with quartz–sericite–pyrite wallrock alteration. Wilton *et al.* (1987) reported slightly elevated precious-metal values at several prospects along the unconformity.

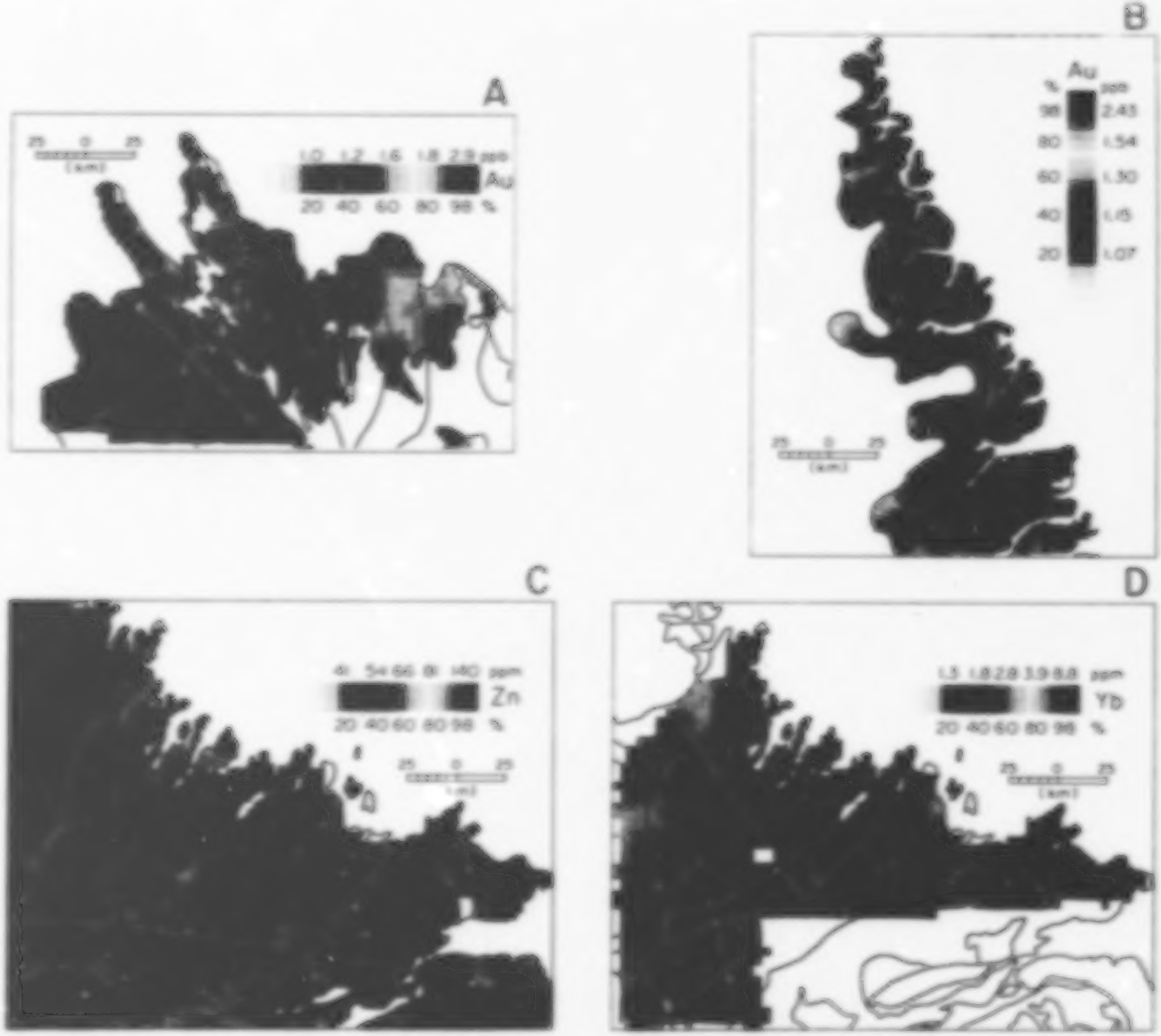

A
25 0 25
(km)
1.0 1.2 1.6 1.8 2.9 ppm
Au
20 40 60 80 98 %
B
Au
% ppm
98 2.43
80 1.54
60 1.30
40 1.15
20 1.07
25 0 25
(km)
C
41 54 66 81 140 ppm
Zn
20 40 60 80 98 %
25 0 25
(km)
D
1.5 1.8 2.8 3.9 8.8 ppm
Yb
20 40 60 80 98 %
25 0 25
(km)

Figure 10. *Details of geochemical maps illustrating anomalies of economic interest. See text for discussion. 10a—Au in lake sediments, western Labrador; 10b—Au in stream sediments in northern Labrador; 10c—Zn in lake sediments in the Central Mineral Belt; 10d—Yb in lake sediments, eastern Central Mineral Belt.*

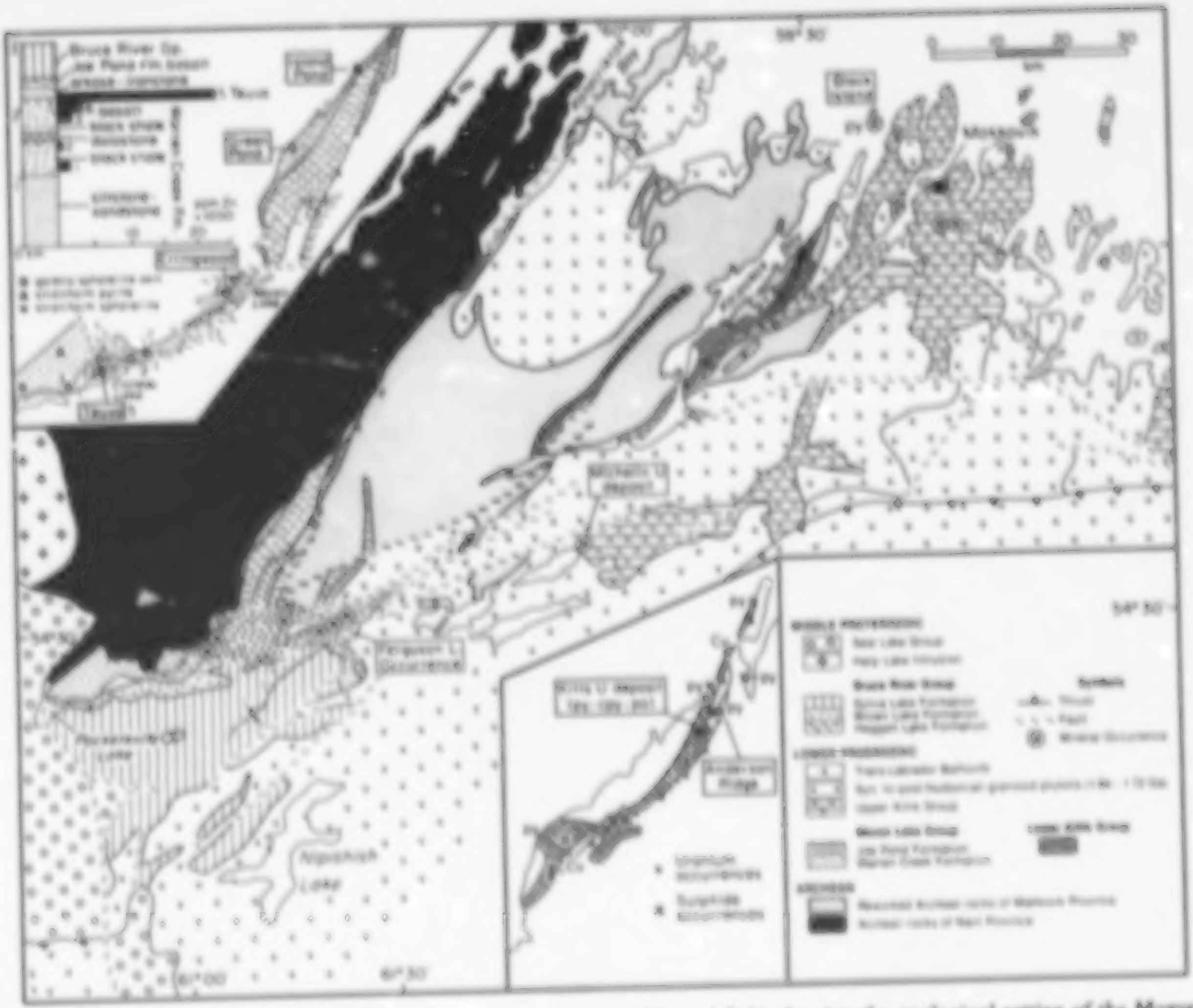


Figure 11. *Geology of the Makkovik Province (eastern Central Mineral Belt) showing the geological setting of the Moran Lake, Aillik and Bruce River groups. Inset at top left shows details of the Moran Lake Group and its mineral deposits (after Ryan, 1984; and North, 1988); inset at bottom illustrates the mineral occurrences of the Lower Aillik Group in the Kitts–Post Hill belt (after Gower et al., 1982).*

The locally elevated gold values associated with the alteration and mineralization suggest that this environment has some potential for gold exploration. Detailed geochemical studies and prospecting might pinpoint targets where detailed exploration is warranted.

Eastern CMB Lode Veins

Gold values up to 8.8 ppm were reported from a quartz vein cutting the Upper Aillik Group near Pomiadluk Point by Wardle and Wilton (1985) (see Figure 21 for location). Anomalous gold values (1 to 2 ppm) were also found in nearby galena–sphalerite-bearing quartz–carbonate–fluorite veins at Big Bight and gabbro-hosted pyritiferous occurrences at Poodle Pond (Wardle and Wilton, 1985; Wilton *et al.*, 1987). The Big Bight occurrences are spatially and probably genetically associated with posttectonic granitoid stocks in the area. One of these, the Round Pond stock (ca. 1.65 Ga) has been studied in detail by MacDougall (1988) who described a porphyry-style mineralization around it. MacDougall and Wilton (1987b) reported the discovery of a 2.5-cm-wide carbonate vein system at Round Pond, which contained up to 7.4 percent Zn and minor Pb, Mo and Au (55 ppb). Adjacent altered country rocks host Au contents of up to 820 ppb and 3 ppm Ag.

Regional lake- and stream-sediment data (Hornbrook and Friske, 1988b) show generally anomalous As values in this area with local enrichments in Sb, Ag, Au, Cu and W.

Bruce River Group

The ca. 1.65 Ga Bruce River Group comprises a basal sequence of terrestrial conglomerates and arkoses (Heggart Lake Formation) that passes upward through sandstones (Brown Lake Formation) into a thick pile of felsic ash-flow tuffs and mafic volcanic flows (Sylvia Lake Formation) (Figure 11). The acid volcanic rocks have a predominantly rhyolite–dacite composition; the mafic rocks have shoshonitic affinities, and are likely to have formed in a mature continental arc environment. This group likely formed in a caldera setting (Ryan, 1984) and is interpreted, along with other 1.65 Ga volcanic groups along the northern side of the Trans-Labrador batholith (MacKenzie Lake group, Blueberry Lake group), to form the volcanic carapace to the batholith (Schärer *et al.*, 1988; Gower, 1990). The chemistry and caldera setting of these rocks are analogous to modern terrestrial volcanic arcs and suggests a similar potential for epithermal, vein-hosted precious-metal mineralization. Exploration to date has been directed at U- and Cu-bearing veins, mainly in the lower (clastic) part of the group with very little work directed toward precious-metal targets.

The only known syn-volcanic mineral occurrence in the Bruce River Group is the Ferguson Lake showing (Figure 11) (Wilton, 1988, *in press*), comprising sphalerite, galena, carbonate and fluorite in a pegmatitic(?) vein. Assay values (Wilton, *in press*) show anomalous concentrations of Au (up to 290 ppb), As (up to 400 ppm), and Sb (up to 340 ppm). The pegmatite may be a feeder to stratigraphically higher felsic volcanic rocks, suggesting a potential for Bonanza-type or epithermal types of precious-metal deposits.

Although the tectonic setting may not be strictly analogous, the style of volcanism is very similar to that of Nevada and New Mexico, where bimodal volcanic rocks similar to the Bruce River Group are host to epithermal gold and silver veins (Sillitoe, 1976; Elston *et al.*, 1976). In these areas, the most significant mineralization can be related to resurgent cauldrons. The gold and silver veins are spatially related to caldera structures, which acted as controls and traps for epithermal mineralization. Elsewhere in the southwestern United States, high-silica rhyolites host Mo, Sn, W and Be (Elston *et al.*, 1976). A reassessment of the Bruce River Group for such environments is in order.

North Labrador Shear Zones

Grassroots gold-exploration targets in northern Labrador are suggested by image analysis of Au and related elements in lake sediments from this area. In particular, there are a number of interesting Au anomalies along the Abloviak shear zone, a major sinistral shear that separates the Nain and Churchill provinces (Figures 6 and 8b). At present, there is no known source for these anomalies. It seems unlikely that they reflect individual gold deposits, as the sample spacing is too wide. However, considering the well-documented relationship between mesothermal gold deposits and major trans-crustal shear zones elsewhere in the Canadian shield and the world, it may be that they reflect hydrothermal systems (or parts of hydrothermal systems), which caused a regional gold enrichment in these areas. Detailed prospecting and geochemical work is needed to fully evaluate these targets.

Grenville

Although there are no known precious-metal occurrences in the Labrador Grenville, discoveries in probably correlative rocks in Scandinavia suggest that such deposits might be present. In the Sveconorwegian Province of Sweden, Au mineralization has been reported from quartz veins. In one example, in the Nyaster area north of Amal, up to 7 ppm gold has been reported from a 0.5-m-wide quartz vein that intrudes mylonitized rocks probably derived from an orthogneiss protolith. The age of the mineralization is not known but is inferred to be Sveconorwegian, perhaps being genetically related to the Ursdan granite nearby to the west.

Recent dating of granitoid plutons of Grenvillian age coupled with regional geological and geophysical interpretation (Gower *et al.*, *in press*,b) suggests that plutonism of this age could be widespread in southern Labrador and adjacent Quebec. If there is a genetic link with such plutonism, there is ample scope for comparable mineralization.

SEDIMENTARY EXHALATIVE BASE METALS

Introduction

Labrador contains a number of Lower Proterozoic shale–sandstone basins preserved within the Churchill, Makkovik, Nain and Grenville provinces (Figure 12). The sedimentary sequences in these basins are generally interpreted to be basin infilling related to extensional tectonics and are locally accompanied by mafic magmatism. Although there are no documented stratiform mineral occurrences in the Labrador Lower Proterozoic clastic basins, analogy with other areas of the world (e.g., Aldridge Formation, B.C., MacArthur Group, N.T., Australia) suggests that several of them apparently contain the essential elements of sedimentary-exhalative (SEDEX) and Besshi-type deposit models.

Basal Clastic Sequences, Central Mineral Belt

The oldest supracrustal rocks in the Central Mineral Belt are Lower Proterozoic clastic sediments and associated mafic volcanic rocks assigned to the Moran Lake and Lower Aillik groups. Both contain stratiform pyritic showings hosted by graphitic argillites (Figure 11). In the Moran Lake Group, base metals are locally associated with these showings (inset, Figure 11). The presence of these showings, and comparison with similar geology in Scandinavia, suggest a potential for exhalative, shale-hosted base-metal sulphides.

The Moran Lake Group is divided into a lower Warren Creek Formation, comprising clastic sedimentary rocks, and an upper Joe Pond Formation comprising mafic volcanic rocks (Ryan, 1984). The Warren Creek Formation is divided

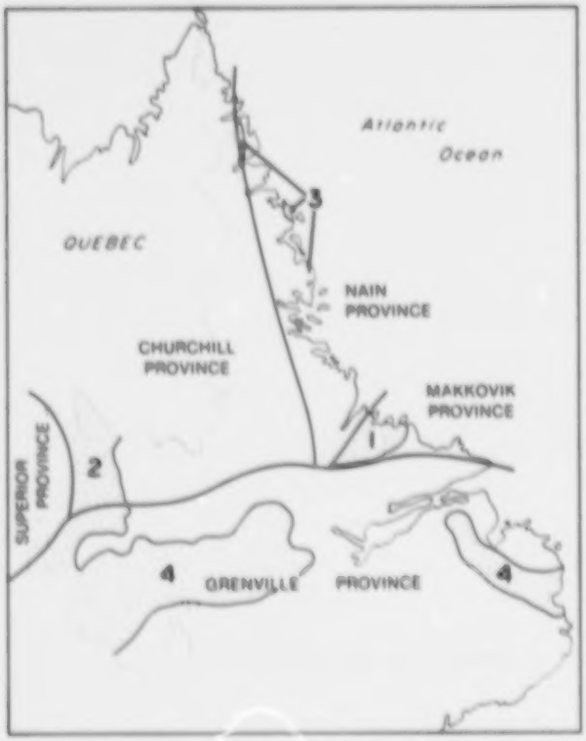


Figure 12. *Target areas for sediment-hosted massive sulphides. 1—basal clastic sequences of the Central Mineral Belt; 2—Labrador Trough; 3—Ramah—Mugford—Snyder groups, northern Labrador; 4—Grenville Province metasedimentary gneisses.*

into a lower member, comprising 180 to 1300 m of dominantly fine-grained feldspathic sandstone and siltstone and a conformable upper member of 550 to 3350 m of dominantly graphitic black shale along with lesser sandstone and siltstone. It is the upper member that hosts the stratiform sulphides (North, 1988; North and Wilton, 1988).

There are more than 16 occurrences of sulphide gossans containing stratiform disseminated to massive pyrite in the Warren Creek Formation shales. Stratiform mineralization in the Warren Creek Formation shales was first reported by Brinex geologists in the 1950's, who discovered and drilled a number of generally base-metal-poor showings. Ryan (1984) interpreted these showings to be distal accumulations related to exhalative processes. New sulphide occurrences were reported by North and Wilton, (1988) and North (1988) following regional metallogenic studies in the area. Perhaps more significantly, these authors reported anomalous base metals from some of these showings, including one zone (the Teuva or Heart Pond showing) that yielded grab samples up to 2.69 percent Zn (inset, Figure 11). North (1988) interpreted these deposits as sedimentary exhalative and presented a model for this mineralization that involved hydrothermal circulation driven by mafic magmas that later erupted to form the Joe Creek Formation basalts.

Although stratiform mineralization is not as widely documented in the Lower Aillik Group, there are a number of pyritic occurrences. The best known are the Anderson Ridge prospect in the Kitts—Post Hill belt and the Black Island occurrence in Kaipokok Bay, both comprising apparently bedded pyritic and pyrrhotitic sulphides hosted by graphitic argillite (inset, Figure 11). The presence of these and other small showings in the area indicates that mineralization processes similar to those in the Moran Lake Group may have been operating here, and suggests an exploration potential for deposits that might contain significant base-metal contents.

Regional lake-sediment geochemical data also indicate anomalous base metals associated with these sequences (Figure 10c). Strong anomalies in Zn, Ag, Ni, Hg, Cu, Sb, Cd and locally As are found over the southwestern part of the Moran Lake Group. Lake sediments over the Lower Aillik Group are strongly anomalous in Zn and enriched in Cu, Pb, Sb, Au, Cr and Ni.

Comparison with equivalent geological units in Scandinavia further emphasize the sulphide potential of the Makkovik Province. Although the Makkovik—Ketilidian Orogen forms a comparatively small part of Laurentia, broadly coeval rocks of the Svecofennian Orogen cover vast tracts of Baltica and include the well-known Skellefte and Bergslagen sulphide districts in Sweden. Massive stratabound polymetallic deposits in the Skellefte district are commonly localized in the contact zone between submarine felsic volcanic rocks and the overlying phyllites or metagreywackes (Pharaoh and Pearce, 1984) and have been interpreted as the product of magmatic processes in a volcanic arc. The Bergslagen district is characterized by Fe—Mn oxide and polymetallic sulphide mineralization. Current models envisage a continental rifting environment in which sedimentary exhalative deposits were associated with early felsic volcanism; as the rift grabens developed and volcanism became less explosive, epigenetic stratiform and massive sulphide mineral deposits were formed in the accumulating overlying sediments (e.g., Parr and Rickard, 1987; Vivallo and Rickard, 1990).

Labrador Trough

The largest lower Proterozoic sedimentary basin in the eastern Canadian Shield is represented by the Labrador Trough. In Labrador, this basin consists of a western component (Schefferville Zone) of predominantly shallow-water sedimentary rocks, and an eastern component (Howse Zone) dominated by deep-water turbidites, shales, basalt flows and massive volumes of gabbroic sills. The two zones are separated by the major Ferrum River thrust fault (Figure 13).

Stratigraphy in the Schefferville Zone consists of basal (rift-related) arkoses (Seward Subgroup) overlain by a shallowing-upward sequence of shale, dolomite and chert breccia of the Attikamagen Subgroup. This is disconformably overlain by the deepening-upward succession of quartzite, ironstone, shale, turbidite and arkose of the Ferriman

Subgroup. The turbidites–volcanic–sill association of the Howse Zone is probably correlative with the Attikamagen Subgroup, although this is by no means certain (Figure 14).

The rocks of the Attikamagen Subgroup (and their Howse Zone equivalents) are believed to have formed during the rift–drift breakup of the Superior craton and represent a well-preserved continental margin sequence (cf. Wardle and Bailey, 1981). The gabbro sill swarm of the Howse Zone is believed to be part of the continent–ocean transition and to represent attempted ocean crust formation in a sediment-dominated environment. Close analogies can be drawn with the Gulf of California (Einsele, 1986). The Howse Zone also contains numerous massive pyrite–pyrrhotite deposits located within graphitic black shale units sandwiched between gabbro sills. These are apparently of a syngenetic nature and contain minor amounts of copper and zinc mineralization (Baragar, 1967; Wardle, 1979a).

The shale formations of the Attikamagen Subgroup, notably the Le Fer and Dolly formations, in the Schefferville Zone are interpreted to have formed on extended continental crust and should have good potential for SEDEX mineralization, although little exploration activity has been targeted at these rocks.

The upper part of the Schefferville Zone, represented by the Ferriman Subgroup, is interpreted as a westward-prograding foredeep (Hoffman, 1987) developed in advance of a thrust stack encroaching from the east. The Menihek Formation shales and turbidites, which form the basinal part of the foredeep, are associated with lake-sediment zinc anomalies that have received extensive industry attention.

Ramah–Mugford–Snyder Groups

These groups occur as remnants of a lower Proterozoic cover sequence on the Nain Craton (Figure 15). Their development was likely broadly coeval with that of the Moran and Lower Aillik groups and possibly the Labrador Trough on the opposite side of the proto-Churchill Province. The basal clastic rocks of the Ramah–Mugford–Snyder sequences show an overall stratigraphic similarity and have been correlated by Smyth and Knight (1978).

The Ramah Group (Knight and Morgan, 1981; Morgan, 1975) is the most extensive unit. At its base it consists of a basal series of dolomitic sandstone, quartzite and dolomite (Rowsell Harbour and Reddick Bight formations) overlain by a series of shallow- to deep-water shales (Nullataktok Formation) including a widespread massive bedded pyrite–chert formation (Figure 16). The pyrite–chert association appears to have formed in a starved, euxinic basin and marks the end of shelf-type shallow-water sedimentation. The Nullataktok Formation is overlain by dolomite debris-flow breccias of the Warspite Formation, which passes up into voluminous turbidites of the Cameron Brook and Typhoon Peak formations. The Nullataktok–Typhoon Peak sequence has been interpreted by Hoffman (1987) as an eastward-prograding foredeep. The Ramah Group has been intruded by gabbro sills, deformed, variably metamorphosed up to amphibolite facies and forms part of an east-verging fold-and-thrust belt developed along the eastern margin of the Churchill Province (the Torngat Orogen).

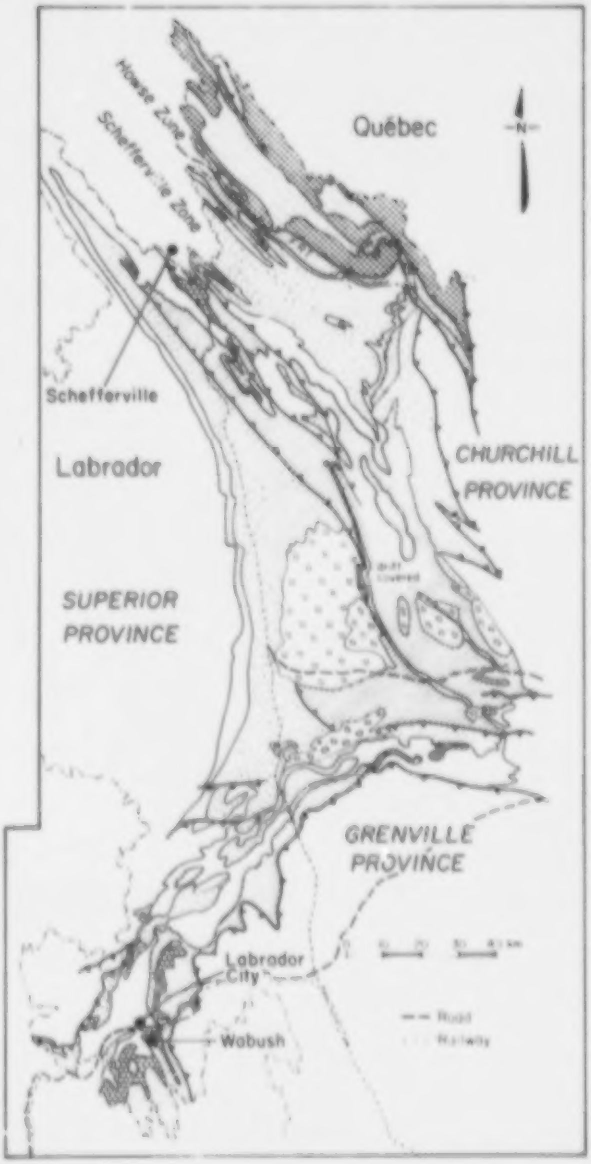


Figure 13. *Geological map of the Labrador Trough showing the shale–sandstone units thought to have potential for sediment-hosted massive sulphide deposits (See Figure 14 for legend.). Note that the Le Fer and Dolly formations of the Attikamagen Subgroup (see Figure 14) are combined on this map. They are generally separated by the Denault Formation dolomite, which in many areas is too thin to be shown at this scale. FRT = Ferrum River thrust.*

The basal Mugford Group consists of terrigenous clastics and shales containing dolomitic and pyritic beds correlated

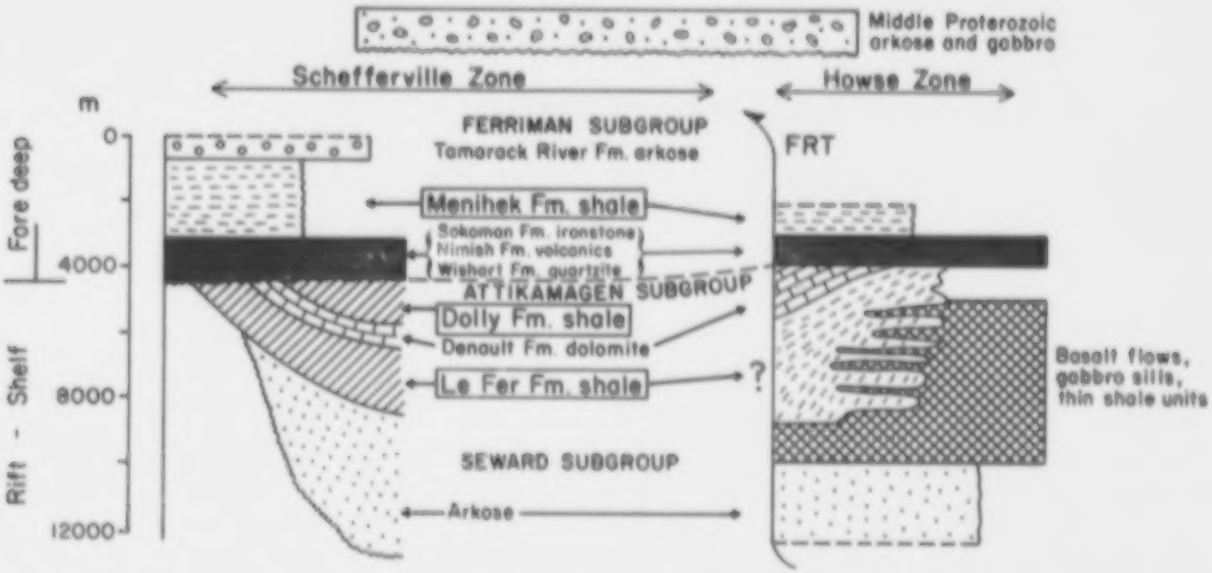


Figure 14. *Schematic stratigraphic sections of the Labrador Trough after Wardle* et al., in press,*b). Shale-dominated units considered to have SEDEX potential are shown boxed in bold type. Vertical scale is approximate. FRT = Ferrum River thrust.*

with those in the Reddick Bight and Nullataktok formations of the Ramah Group (Smyth and Knight, 1978; Figure 17). These are overlain by a thick pile of submarine, followed by subaerial, mafic volcanic flows, breccias and sills. The sequence is metamorphosed to greenschist facies and has been affected by open upright folds and normal faulting.

The Snyder and the overlying Falls Brook groups form an aerially restricted, wedge-shaped sequence underlying the northern edge of the Middle Proterozoic Kiglapait Intrusion. They have been contact metamorphosed at pyroxene–hornfels facies by the intrusion. Primary depositional features are well preserved in both Snyder and Falls Brook groups. A correlation with the basal Ramah and Mugford groups has been suggested by Smyth and Knight (1978) (Figure 17), although this correlation was later questioned by Berg (1983). Speer (1978) described a graphite–sulphide-bearing siltstone within the Snyder Group that contains abundant pyrrhotite, pyrite and sphalerite with chalcopyrite.

The pyrite bed of the Ramah Group is the most obvious target for sediment-hosted exhalative sulphides and is associated with several Pb–Zn stream-sediment anomalies (MacLeod, 1984, 1985). Early investigations of this unit did not return significant base- or precious-metal values although traces of chalcopyrite were noted locally (Douglas, 1953; Morgan, 1975) and several grassroots exploration programs have been directed at the pyrite bed without discovering significant base-metal mineralization. However, much of the Ramah Group remains to be explored. The similarity of the basal Mugford Group to the basal Ramah Group sequence suggests a similar potential. The presence of a thick volcanic pile in the Mugford Group may indicate higher heat-flow conditions and possibly enhanced hydrothermal activity. There are widespread polymetallic lake-sediment anomalies in Cu, Pb, Ni, Co, Mo, U, Zn, As, and Ag over the Mugford Group. Pb and As are locally enriched in lake sediments over the Ramah Group.

Grenville Metasedimentary Gneiss Terranes

Although there are no base-metal occurrences of documented sedimentary exhalative origin in the Grenville Province in Labrador, there are a number of sulphide-bearing mineral occurrences (cf. Gower and Erdmer, 1984). Geological and geochemical observations suggest an exploration potential for this deposit type.

A good example is provided by the Paradise metasedimentary gneiss belt in southeastern Labrador (Figures 6 and 12). Gower *et al.* (1987) described this belt as including gneisses of supracrustal origin dominated by pelitic and semipelitic rock types and with lesser associated amphibolite, calc-silicate rock and chert. Rocks have been metamorphosed in the amphibolite facies and are characteristically cordierite-bearing (Gower *et al.*, 1987). The amphibolites are dominantly banded, fine- to medium-grained rocks comprising mainly plagioclase and hornblende. Pillows are locally preserved, and elsewhere mafic dykes seem to be spatially associated with banded amphibolite. Recent geochemical analyses of unequivocal pillows from the Dead Islands suggest that they are mildly alkalic basalts (Gower and Swinden, *this volume*). Possible tectonic models include an oceanic island environment, an intra-oceanic rift (e.g., enriched major ocean or back-arc spreading centre) or rifting of a passive continental margin.

The overall depositional environment of the Paradise metasedimentary gneiss belt, therefore, appears to be

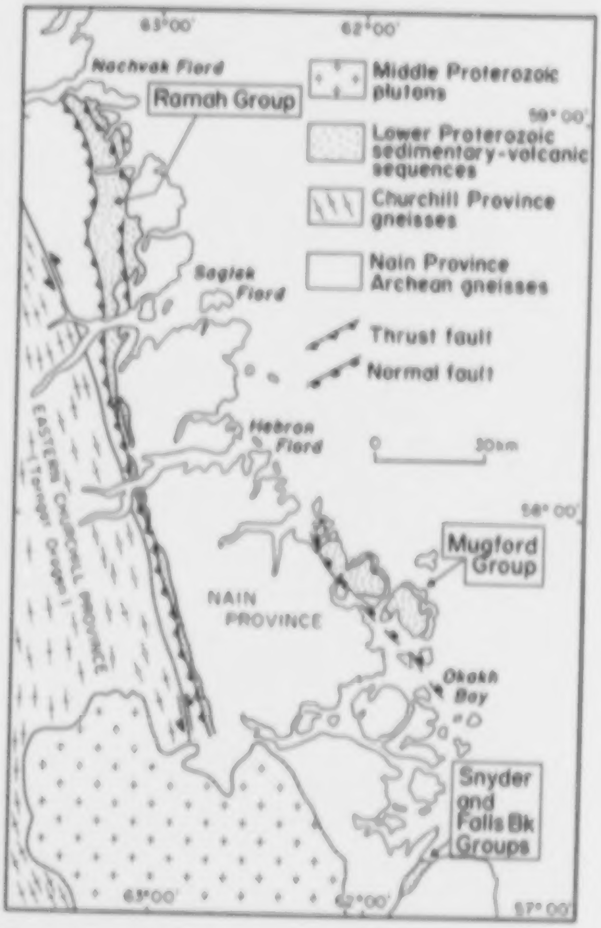

63°00'
62°00'
Nachvak Fiord
Ramah Group
Middle Proterozoic plutons
59° 00'
Lower Proterozoic sedimentary-volcanic sequences
Churchill Province gneisses
Saglek Fiord
Nain Province Archean gneisses
Thrust fault
Normal fault
Hebron Fiord
0
30km
58° 00'
Mugford Group
EASTERN CHURCHILL PROVINCE (Torngat Orogen)
NAIN PROVINCE
Okak Bay
Snyder and Falls Bk Groups
63°00'
62°00'
57° 00'

Figure 15. *Geological setting of the Ramah, Mugford and Snyder groups in northern Labrador. See Figure 4 for locations.*

extensive sedimentation accompanied by mafic volcanism in an oceanic rifting environment (Gower and Swinden, *this volume*). Such environments are known elsewhere to host both sedimentary exhalative and Besshi-type massive sulphide deposits (Mitchell and Bell, 1973; Slack and Shanks, 1989). Large massive sulphide deposits can typically survive very intense metamorphism and deformation intact (e.g., Broken Hill), and if such deposits were generated in the Grenville Province, there seems little reason to believe that they would not still be present. Regional lake-sediment data suggest the southeastern part of this belt as a primary target, having strongly anomalous Cu, Ni, Co and Hg with locally anomalous Pb and Mo.

Although the Paradise metasedimentary gneiss belt is the best-documented example, it should be noted that similar, less-studied rocks outcrop over vast areas of the northern Grenville Province in central and western Labrador (Figures 5 and 12). Consideration of regional lake-sediment data might provide rationale for focusing exploration in these regions in a grassroots exploration effort.

PROTEROZOIC VOLCANOGENIC MASSIVE SULPHIDES

Introduction

Proterozoic rocks in Labrador do not contain many well-documented mineral occurrences that are demonstrably of volcanogenic massive sulphide type. Although correlations with other areas suggest that an exploration potential might exist (e.g., the previously mentioned correlation between the Skellefte District, Sweden and the Makkovik Province), specific environments with exploration potential are not well documented. Present data suggest two environments that might bear exploration for this deposit type; the Letitia Lake Group in the Central Mineral Belt and the Blueberry Lake group in western Labrador (Figures 6 and 18).

Letitia Lake Group

The Letitia Lake Group of central Labrador consists of ca. 1.32 Ga peralkaline volcanic rocks intruded by cogenetic peralkaline syenites and alkaline plutonic rocks (see Figures 6 and 22 for locations). The volcanic rocks are typically quartz–feldspar porphyritic ash-flow tuffs and associated rocks, and contain some pyritiferous zones that appear to represent syngenetic mineralization of VMS type (Wardle and Wilton, 1988). The group is also cut by quartz vein systems, associated with pyrite alteration and minor galena mineralization, which are probably of Grenvillian age. Reconnaissance sampling of both massive sulphides and vein systems has not revealed any significant precious- or base-metal values, although Wilton (*in press*) reported 11.5 ppm Ag in a grab sample from a sulphide-bearing vein. However, regional lake-sediment data reveal local anomalies in Zn, Pb, Cd, Ag ± As and there would appear to be potential for further exploration.

Blueberry Lake Group

The Blueberry Lake group of western Labrador (Figure 6) is believed to be correlative with the ca. 1.65 Ga Bruce River Group and to be similarly related to the Trans-Labrador batholith. The northern part of the Blueberry Lake group consists of felsic volcanic rocks, predominantly tuffs of latite–rhyolite composition, intercalated with various breccias, sedimentary and intrusive units. These pass westward into a dominantly sedimentary succession of greywacke, slate and conglomerate (Wardle, 1979b). The predominantly subaqueous character of the Blueberry Lake group distinguishes it from the Bruce River Group and suggests that it may have greater potential for volcanic- or sediment-hosted massive sulphide mineralization. Moderate lake-sediment geochemical anomalies in As, Zn, Ni and Pb are present over the group.

PLATINUM GROUP ELEMENTS (PGE)

With the exception of the PGE-enriched Cu–Ni sulphide deposits in the Florence Lake greenstone belt (previously

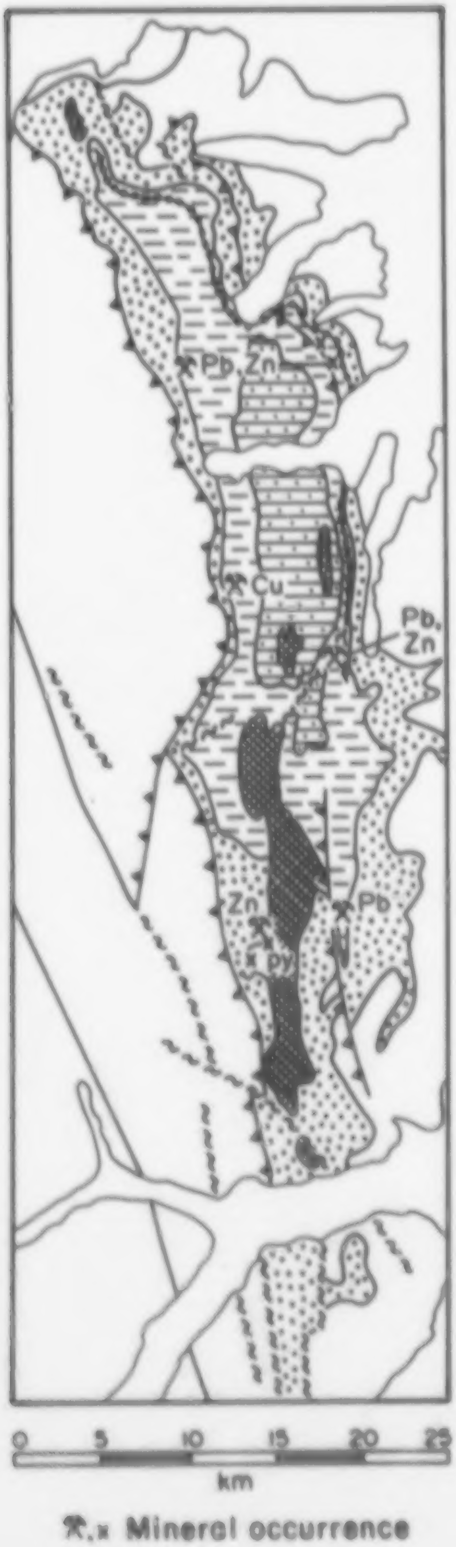

Pb, Zn
Cu
Pb, Zn
Zn
Pb
x py
0
5
10
15
20
25
km
⚒,x Mineral occurrence
LEGEND
Gabbro sills
Cameron Brook and Typhoon Peak formations
Warspite and Nullataktok formations
Reddick Bight and Rowsell Harbour formations
pyrite – chert bed

Figure 16. *Geology of the Ramah Group (after Morgan, 1975). Mineral occurrences after MacLeod (1984, 1985).*

mentioned) and some mildly PGE-enriched sulphide showings in the Harp Lake anorthosite intrusion, there are no known PGE occurrences in Labrador. However, comparison of Labrador geology with environments known to be productive elsewhere in the world suggests that there is a significant grassroots potential for PGE exploration. The growing strategic importance of this group of elements coupled with the discovery of a significant new PGE occurrence in the Labrador Trough in adjacent Quebec prompted Wardle (1987) to review possible PGE exploration targets in Labrador. This comprehensive review remains the definitive document on PGE potential in Labrador and the reader is referred to it for further information and references.

Wardle (1987) recognized six bedrock geological environments in Labrador that might host PGE concentrations (Figure 19):

1) Massif-type anorthosite plutons: Large anorthosite plutons of this type are widespread in the Nain, Churchill and Grenville provinces. Small Cu–Ni showings (stratiform zones of disseminated chalcopyrite, pyrrhotite and minor pentlandite) are known in the Harp Lake intrusion, which locally have elevated PGE values. Other massif-type anorthosite plutons have received little attention and their potential is not known.

2) Layered gabbroic plutons: The largest layered intrusion in Labrador is the Middle Proterozoic Kiglapait Intrusion (Morse, 1969) near Nain. Significant analogies can be drawn between the preserved parts of this intrusion and the productive horizons in the Bushveld and Stillwater intrusions (Wardle, 1987) and minor showings of pyrite, pyrrhotite, chalcopyrite are known. No PGE enrichments have been reported. The discovery of stratiform gold and PGE group enrichments associated with sulphides in the Tertiary

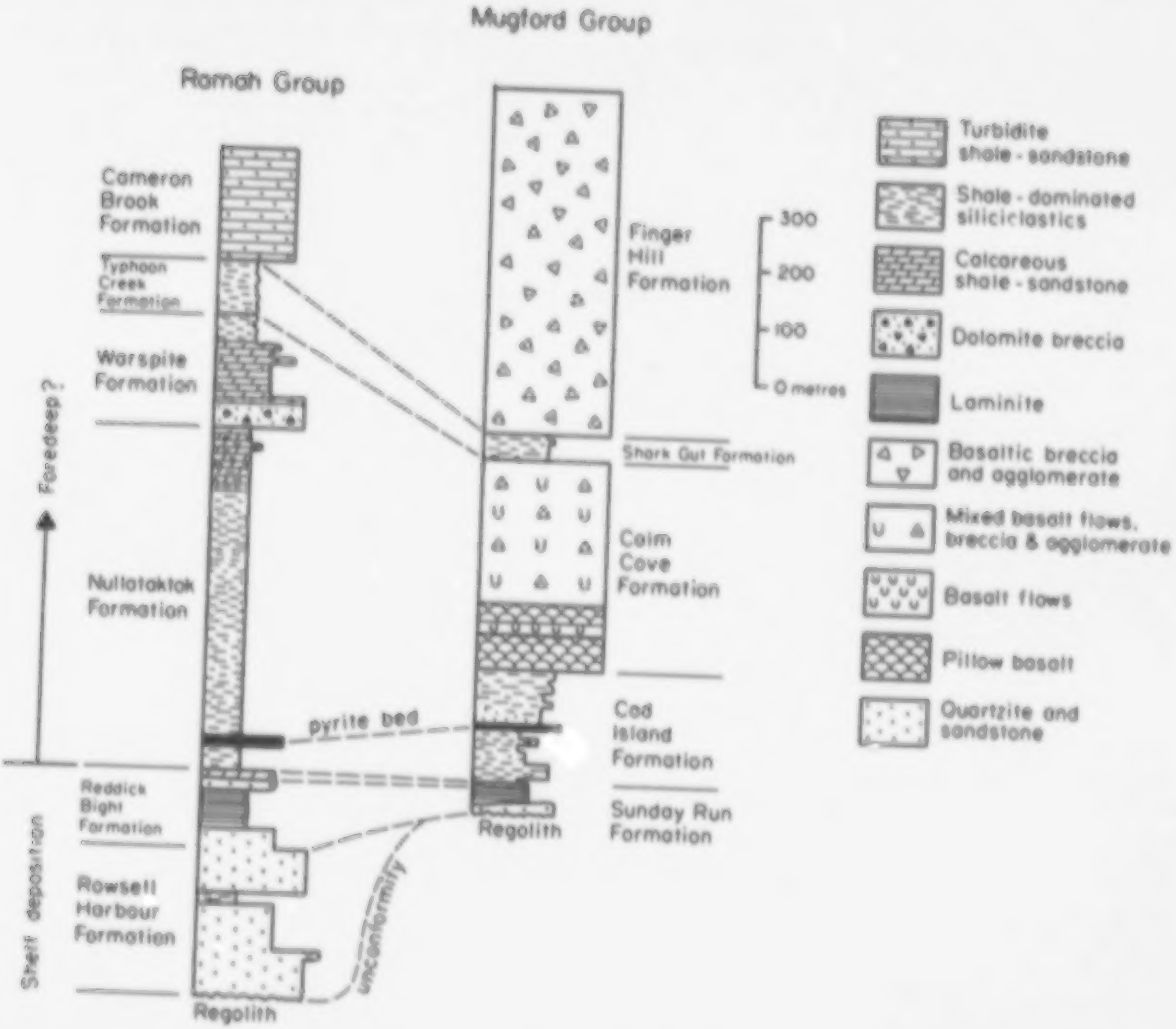

Mugford Group
Ramah Group
Cameron Brook Formation
Typhoon Creek Formation
Warspite Formation
Nullataktok Formation
Reddick Bight Formation
Rowsell Harbour Formation
Regolith
Foredeep?
Shelf deposition
pyrite bed
unconformity
Finger Hill Formation
Shark Gut Formation
Calm Cove Formation
Cod Island Formation
Sunday Run Formation
Regolith
300
200
100
0 metres
Turbidite shale - sandstone
Shale - dominated siliciclastics
Calcareous shale - sandstone
Dolomite breccia
Laminite
Basaltic breccia and agglomerate
Mixed basalt flows, breccia & agglomerate
Basalt flows
Pillow basalt
Quartzite and sandstone

Figure 17. *Simplified stratigraphic sections of the Ramah and Mugford groups (after Smyth and Knight, 1978). Interpretation of rift versus foredeep setting is taken from Hoffman (1987). Gabbro sills, which are abundant in both groups, are not shown.*

Skaergaard intrusion of East Greenland (Neilsen and Schønwandt, 1990) suggests the possibility that the Kiglapait Intrusion may host similar mineralization. Both the Kiglapait and Skaergaard are classic examples of tholeiitic magma fractionation within a well-defined magma chamber. However, the Skaergaard parent magmas appear to have been more silica-saturated and more oxidized that the Kiglapait magmas (cf. Morse, 1980).

Other minor gabbroic intrusions associated with anorthosite suites occur in the Nain Plutonic Suite, the Harp Lake intrusion and the Atikonak River massif.

3) Massive to weakly layered plutons: This includes widespread intrusions of gabbro and norite within the Grenville Orogen, including the Shabogamo Intrusive Suite, the Michael Gabbro, gabbro-norites of the Red Wine Mountains, and the White Bear Arm gabbro. Minor Cu and Ni mineralization is present locally but no PGE enrichments have been documented.

4) Gabbro-ultramafic sheets and sills: This class comprises high-level intrusions located within or adjacent to supracrustal sequences containing comagmatic volcanic rocks. They include suites ranging from Archean to Middle Proterozoic age in three widely separated areas:

i) Gabbroic and ultramafic sills are widespread in the Quebec portion of the Labrador Trough where a number of significant PGE occurrences, including the Retty Lake deposit

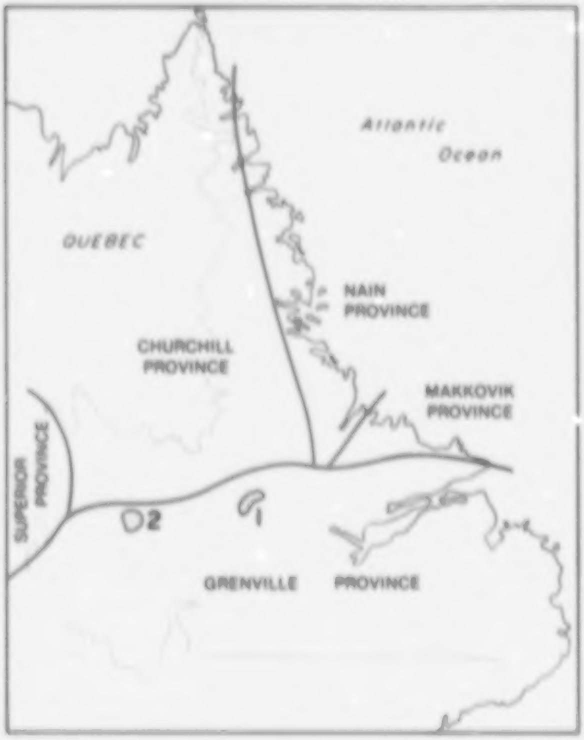


Figure 18. *Target areas for Proterozoic VMS deposits. 1–Letitia Lake Group; 2–Blueberry Lake group.*

near Schefferville, are associated with ultramafic sills. The southern extensions of these sills into Labrador are dominantly gabbroic in composition and host minor magmatic sulphide occurrences. Geochemical investigations (Findlay *et al.*, 1988) have not yielded evidence of PGE enrichment.

ii) Basaltic rocks of the Seal Lake Group were erupted into a transitional shallow-marine to terrestrial environment during a period of anorogenic crustal rifting. Wardle (1987) noted that, in this sense, they are similar to basaltic sequences that host the giant Noril'sk deposits in western Siberia. However, recent geochemical studies of the Seal lake basalts and associated diabase (Wilton, 1989b) have not returned evidence of anomalous Ni sulphide, chromite or PGE concentrations.

iii) Cu–Ni mineralization is known to be associated with ultramafic sills in the Archean greenstone belts of the southern Nain Province (see above) and is locally enriched in PGE.

5) Archean layered anorthosite–gabbro–ultramafic intrusions: These intrusions occur as sheet-like bodies in reworked Archean rocks of the northeastern Churchill Province, and as podiform bodies in the Nain Province. Their presence is reflected in high Ni and Co concentrations in lake sediments and they are geologically akin to the Fiskanaesset Complex in adjacent Greenland, which hosts chromite and associated low-grade PGE mineralization. Wilton and Wardle (1990) have described pyrrhotite and chalcopyrite in sulphide-rich horizons in layered anorthosite at Eclipse Harbour.

6) Hornblende gabbro–diorite–monzonite intrusions: The ca. 1.65 Ga Adlavik Intrusive Suite of eastern Labrador is characterized by late hydrous phases, which locally contain pyrite and chalcopyrite. The fluid-rich nature of these late phases may indicate a potential for deuteric or hydrothermal concentration of PGE, although unpublished data from sulphide-bearing pegmatitic concentrations collected by one of us (A.K.), in 1987, yielded no anomalous concentrations of the PGE.

GRANOPHILE ELEMENTS

Introduction

Granitoid rocks of various ages and petrogenetic affiliations are widespread in all of the orogens of Labrador (Figures 5 and 6). Areas of potential granophile mineralization are shown in Figure 20. A defined potential is indicated in the eastern part of the Trans-Labrador batholith by showings of Mo, U and other granophile elements and in the Strange Lake and Letitia Lake areas by rare-metal deposits in peralkaline rocks and further potential in unexplored areas is indicated by lake-sediment geochemical data (McConnell and Batterson, 1987; McConnell, 1988, 1989; see Figure 4a). The efficacy of geochemistry in granophile-element exploration in Labrador is indicated by the fact that both Letitia Lake and Strange Lake area rare-metal deposits were discovered through drainage geochemical surveys (Brummer, 1960; Zajac *et al.*, 1984, respectively). Potential, in as yet underexplored areas of the Churchill and Grenville orogens, is further suggested by comparison with correlative areas in Scandinavia.

Eastern Makkovik Province

There are numerous showings and deposits of uranium, fluorite, molybdenite and base metals in the eastern part of the Makkovik Province, dominantly within supracrustal rocks of the Upper Aillik Group (Figure 21). Previous models for mineralization in this area (e.g., Gandhi, 1978; Gower *et al.*, 1982) attributed metallogenesis to syn-volcanic processes during formation of the Upper Aillik Group. As a result, granitoid rocks and their surroundings have received very little attention, particularly in the eastern zone of the Makkovik Province. However, recent detailed studies (Wilton, *in press;* MacDougall and Wilton, 1987a; MacKenzie and Wilton, 1987; Wilton and Wardle, 1987) have shown, that many showings are spatially and probably genetically related to late-evolved granitoids in the area (cf. Ryan, 1977). Mineralization includes endocontact mineralization within the granitoid bodies and exocontact mineralization in the country rocks, locally associated with pegmatite and aplite bodies.

Kerr (1987; 1988; *in preparation*) carried out a detailed geochemical and isotopic study of the complex granitoid batholiths in the eastern part of the Makkovik Province and detailed the characteristics of evolved granitoids associated with mineralization. These granitoids show a number of geochemical characteristics indicative of metallogenic 'specialization' including: i) high SiO_2 and depletion in CaO, MgO and FeO; ii) enrichment in incompatible elements; iii) local enrichment in ore elements; iv) extreme depletion in compatible elements; v) decoupling of major- and trace-element variation indicated by disturbance of expected fractionation trends; vi) evidence of volatile activity; and, vii) spatial associations with vein systems, alteration and mineralization. Geochemical features noted above are also shown by several granite bodies that are not known to be associated with mineralization.

One of the best examples of this type of mineralization is a zoned mineral district hosted by a vein swarm around a small stock in the Round Pond area assigned to the ca. 1.65 Ga Monkey Hill Intrusive Suite (Figure 21). MacDougall (1988) described a metallogenic zonation developed around the pluton ranging from proximal Mo−(W)−Cu−F to intermediate carbonate-hosted Zn−Pb to distal U−Zn mineralization. Associated alteration minerals are typical of a skarnoid origin.

Although U, Mo and the base metals are the principal established commodities, other granophile elements such as Sn, W and the rare-earth−rare-metal suite might also be concentrated in this area. MacDougall (1988) reported grains of scheelite associated with granophile sulphide veins in the Round Pond area. Kerr (1988) documented Sn enrichment (116 g/t Sn) in a small endocontact Cu−Pb showing on Burnt Island (Figure 21), and some granitoid suites are enriched in Sn relative to regional background. Many granites in the Makkovik Province have compositions that evolve to weakly peralkaline compositions and analyses of up to 4700 ppm Zr, 400 ppm Y, 1300 ppm La and 1200 ppm Ce have been recorded (Kerr, *in preparation*). Lake sediments in this area are strongly anomalous in Yb and Tb (as strongly as at Strange Lake; Figure 10d) and elevated values of Zn, Pb and other granophile elements; F is greatly elevated in lake waters.

In summary, granites of at least two different ages are associated with mineralization in the eastern Central Mineral Belt. The geochemical characteristics of the mineralized suites are also shared by suites that, as yet, contain no known mineralization. The best exploration potential appears to be in areas that represent high crustal levels where contacts with country rocks are preserved. Regional lake-sediment and water data, as well as locally available detailed geochemical survey data, could aid substantially in target selection in this area as they closely reflect both the local geology and the mineralization (Kerr and Davenport, *in press*).

Rare Metals and Rare Earths in Peralkaline Rocks

The discovery of the Strange Lake Zr−Y−Nb−Be−REE deposit (Figure 6) in 1979 sparked renewed interest in Labrador as a target for rare-metal−rare-earth mineralization. Other rare-metal−rare-earth showings in Labrador include: the Two Tom Lake, Mann #1, Mann #2 and Michelin Nb−Be±Y showings, SW Ten Mile Lake Y showing and the Red Wine North Zr±Y showings, all occuring (with the exception of the Red Wine North occurrence) in the Letitia Lake area (Figure 22), and several small Zr−Nb−Y−REE showings in the Flowers River area (Figure 6) (Miller, 1988). All of these showings are hosted by peralkaline felsic volcanic rocks, (i.e., trachytes, rhyolites) or related subvolcanic intrusions, (i.e., quartz syenites and granites, undersaturated syenites). In addition to known showings, geochemically anomalous concentrations of rare metals in peralkaline volcanic rocks have been reported from the Makkovik area (see above) and from near Fox Harbour on the south Labrador coast (Meyer and Dean, 1988; Figure 20).

The Labrador rare-metal−rare-earth showings are all Middle Proterozoic (Letitia Lake Group, 1327±4 Ma, Hill and Thomas, 1983; Arc Lake Pluton, 1337$^{+7}_{-2}$ Ma, Gandhi *et al.*, 1988; Flowers River Igneous Suite, 1271±15 Ma, Hill, 1982; Strange Lake Complex, 1271±31 Ma, Currie, 1985). They are interpreted to record a crustal uplift-rifting event (Hill and Miller, *in press*), which can be traced throughout Greenland, Scandinavia and into interior North America (Aberg, 1988; Emslie, 1978; Bickford *et al.*, 1986). The magmatic products of this event include peralkaline and alkaline magmas of mafic and felsic compositions, which originated in the mantle or formed by mantle processes and were emplaced into high crustal levels. Rare-metal−rare-earth mineralization is commonly associated with the felsic, highly evolved, phases.

Rare-metal−rare-earth mineralization in Labrador occurs in several modes including: 1) pegmatite−aplite veins and lenses, 2) disseminated zones at or near the contacts of late-stage intrusions and, 3) stratiform disseminated mineralization in near-vent flows (Miller, 1988). The mineralization in all of these modes is thought to result from the concentration of incompatible elements in the roof zones of high-level magma chambers with fluids rich in volatile elements such as F and H_2O. Mineralized veins, pegmatites, small-volume volcanic flows and small late-stage stocks are all fed from this enriched roof zone of the magma chamber.

The Strange Lake deposit was discovered as a result of follow-up work of a F and U anomaly delineated in a regional lake-sediment−water survey (Geological Survey of Canada, 1979). Showings in the Letitia Lake area were discovered as a result of follow-up on a Zn anomaly in stream-sediment survey (Mann #1, Mann #2 and Michelin showings, Brummer, 1960) and through follow-up of an airborne radiometric survey (Two Tom Lake showing; Smith, 1968). Results of recent lake-sediment−water (McConnell and Batterson, 1987; McConnell, 1988) and till geochemical surveys (Batterson, 1989a, b) in both the Letitia Lake and Strange Lake areas indicate that both regional and detailed follow-up lake-sediment and till surveys for elements such as Be and Y are good exploration methods for rare-metal−rare-earth deposits in Labrador.

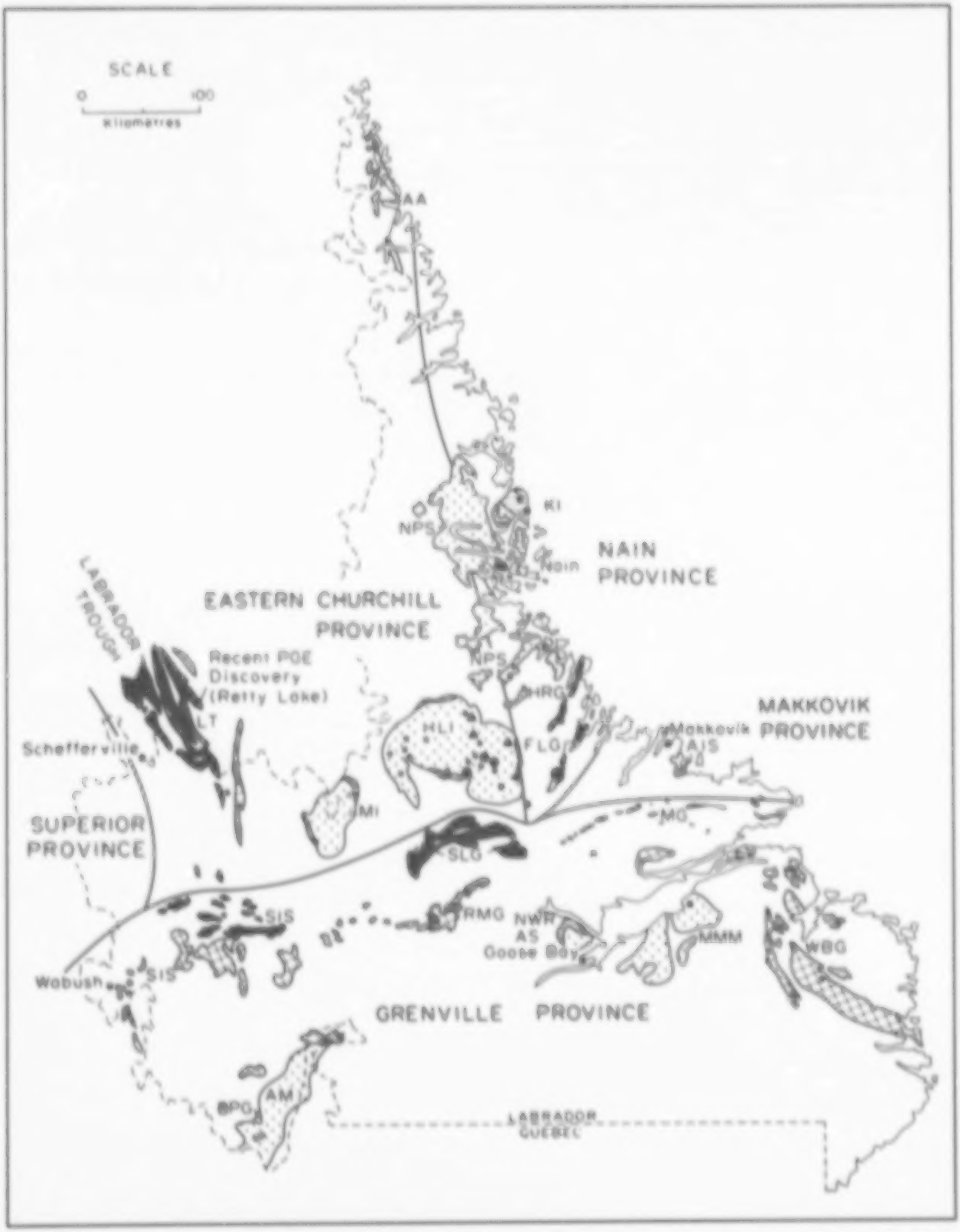

SCALE
0
100
Kilometres
AA
KI
NPS
Nain
NAIN PROVINCE
LABRADOR TROUGH
EASTERN CHURCHILL PROVINCE
Recent PGE Discovery (Retty Lake)
NPS
HRG
MAKKOVIK PROVINCE
Makkovik
AIS
HLI
FLG
LT
Schefferville
MI
MG
SUPERIOR PROVINCE
SLG
LEV
SIS
RMG
NWR
AS
Goose Bay
MMM
WBG
Wabush
SIS
GRENVILLE PROVINCE
AM
BPG
LABRADOR
QUEBEC

Figure 19. *Potential environments for Platinum Group Element mineralization in Labrador (after Wardle, 1987). Individual units denoted by letter codes are identified in the legend opposite.*

Legend for Figure 19

MASSIF-TYPE ANORTHOSITE PLUTONS

▦ NPS – Nain Plutonic Suite, HLI – Harp Lake Intrusion, MI – Michikamau Intrusion, AM – Atikonak massif, MMM – Mealy Mountains massif

▨ *Marginal zone gabbroic rocks*

LAYERED GABBROIC PLUTONS

▤ KI – Kiglapait Intrusion, NWRAS – North West River anorthositic suite, BPG – Beaver Pond gabbro

MASSIVE TO WEAKLY LAYERED PLUTONS

▩ *Generally overprinted by strong deformation and metamorphic recrystallization* SIS – Shabogamo Intrusive Suite, RMG – Red Wine Mountains gabbronorite, MG – Michael Gabbro, WBG – White Bear Arm gabbro.

GABBRO TO ULTRAMAFIC SILLS AND SHEETS

▧ *Gabbro*
▨ *Ultramafites*
LT – Labrador Trough, SLG – Seal Lake Group, FLG – Florence Lake Group, HRG – Hunt River group, SIS – Shabogamo Intrusive Suite

☐ **ARCHEAN LAYERED ANORTHOSITE – GABBRO – ULTRAMAFIC INTRUSIONS (AA)**

HORNBLENDE GABBRO – DIORITE – MONZONITE INTRUSIONS

☒ AIS – Adlavik Intrusive Suite

SYMBOLS

Prospect	*Showing*	
●	•	*Cu – Ni and Ni mineralization; chiefly chalcopyrite and pyrrhotite including minor pentlandite*
▲		*Cu, Ni mineralization containing accessory PGE values*
	●	*Cu mineralization; chiefly chalcopyrite, pyrrhotite and pyrite*

Rapakivi Granites in the Churchill Province

The Middle Proterozoic granitoid rocks that are associated with the gabbro–anorthosite intrusions of central and northern coastal Labrador, traditionally referred to as adamellites (cf. Wheeler, 1960), are areally extensive, underlying much of the area inland from Davis Inlet and as far north as Okak Bay. They comprise four large composite bodies–Notakwanon, Mistastin, Makhavinekh and Umiakovik (Figure 23)–all exhibiting to some extent the texture, mineralogy and geochemical characteristics of the classic rapakivi granites of the Baltic Shield, which occur in a geologically equivalent environment (cf. Rämö and Haapala, *in press*; Ryan, *in press*).

The rapakivi granites of northern Labrador are virtually unexplored and contain no known showings. However, within the last twenty years, greisen veins, hosting cassiterite, wolframite, Be-minerals and sulphides have been found to be associated with topaz-bearing, geochemically anomalous late-stage granites of the Finnish rapakivi batholiths (Haapala, 1988). In addition, veins carrying granophile and base metals occur in and around the margins of some Finnish batholiths. The geological equivalence of the Labrador and Finnish rapakivi granites, the likelihood that they represent the same or a very similar magmatic event, and the documented metallogenic significance of the latter, suggest that granophile mineralization might be expected to be associated with these rocks in Labrador. In this regard, it is interesting that the Umiakovik body has an associated strong F anomaly in lake water.

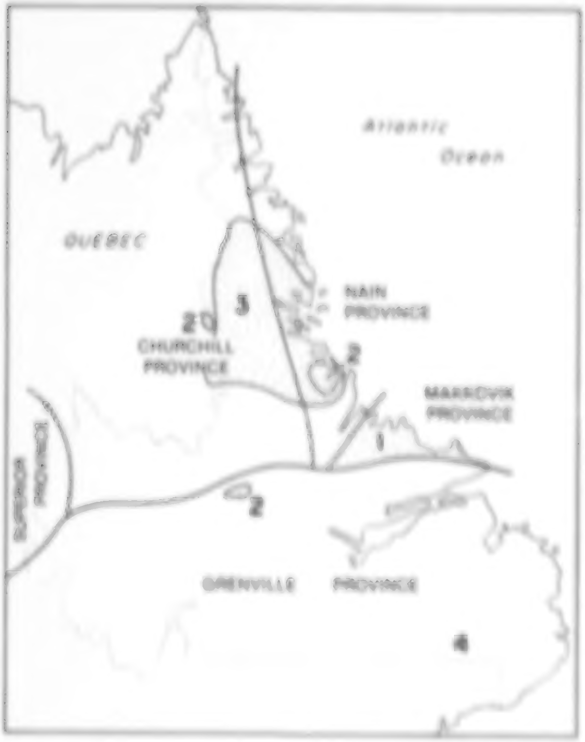


Figure 20. *Target areas for granophile elements. 1—Makkovik Province; 2—rare metals associated with peralkaline rocks; 3—rapakivi granites; 4—southern Grenville Province.*

Grenville Granites

Until very recently, very little was known of the nature or possible economic potential of granitoid rocks in the Grenville Province of Labrador. The extent of middle Proterozoic anorogenic plutonism in eastern Laurentia is presently unknown, mainly because it is most likely to be found in the unmapped area of the southernmost Grenville Province in Labrador. However, recent U–Pb studies in the Pinware terrane (southern Labrador, Figure 6) have identified a granitoid plutonic event at ca. 1.5 Ga, suggesting a correlation with anorogenic plutonism of similar age in Scandinavia and the mid-west U.S.A. In the U.S.A., in particular, such plutonism has been linked with magmatic and hydrothermal Fe and Cu–Fe deposits of the St. Francois terrane in southeast Missouri. This area is also known for Sn–W–Ag–Pb–As–Sb deposits in polymetallic quartz veins, which are considered to be genetically related to the granitic plutonism (e.g., the Silver Mine district; Kisvarsanyi, 1988; Sims *et al.*, 1987).

The likelihood that Grenvillian plutonism is widespread in the southernmost part of the eastern Grenville Province (Gower *et al.*, *in press*,b) suggests a previously unrecognized mineral potential. The granites are enriched in LIL elements and are known to have radio-element anomalies associated with them locally (cf. Gower *et al.*, 1985; Gower and Loveridge, 1987). In addition, lake sediments north and south of Lake Melville carry U anomalies associated with granites and diatexites, and lake waters and sediments over the southern Grenville Province are locally anomalous in F and U+Mo, respectively. In the Sveconorwegian Province in Scandinavia, radio-element anomalies are widespread, especially west of the Mandal–Ustaoset line (Sigmond, 1985), which correlates approximately with the area of extensive Grenvillian plutonism in Labrador. There are widespread Mo anomalies associated with the Scandinavian granites and molybdenite has been reported in late-stage veins within some of the posttectonic granites (e.g., Blomskog granite; Lindh, 1990).

INDUSTRIAL MINERALS

Introduction

Labrador is a storehouse of industrial minerals. Whereas the remoteness of the country has limited the development of these commodities in the past, recent work has shown that the quality of many of these deposits is sufficiently high to warrant serious attention. Exploration in the 1980's has focused on areas with existing infrastructure, road and rail links, (i.e., western Labrador), and on areas with easy access (i.e., the north and south Labrador coast) (Figure 24). The sections below summarize some of the industrial-minerals development opportunities that have been identified in recent years.

Silica in Western Labrador

A reconnaissance study of high-purity quartzites of the Wishart Formation (Figure 25) was carried out in the vicinity of Labrador City by Dean and Meyer (1985). Results of a chip-sampling program (Meyer and Dean, 1986) identified several prospects, one of which was drilled in 1986 (Meyer and Dean, 1987). Geochemical analyses of the drill core show that the quartzite meets requirements for a variety of silica-based products. The availability of cheap hydroelectricity from Churchill Falls, means that the economics of producing commodities such as silicon metal in western Labrador could be very attractive (Fenco-Lavalin, 1988).

Drilling was also carried out on a unique deposit of friable quartzite (Fermont Highway silica sand deposit) believed to have resulted from deep Cretaceous weathering of the quartzites (Meyer and Dean, 1987). This deposit, which could be hydraulically mined, has very high whiteness, and preliminary results show that it would require little processing to achieve total impurity levels of less than 250 ppm.

Graphite–Western and Northern Labrador

The discovery of the Lac Knife graphite deposit near Fermont, Quebec, by Mazarin Incorporated sparked exploration for graphite in western Labrador. This large-flake deposit, which averages 16 percent graphite, occurs in fine-

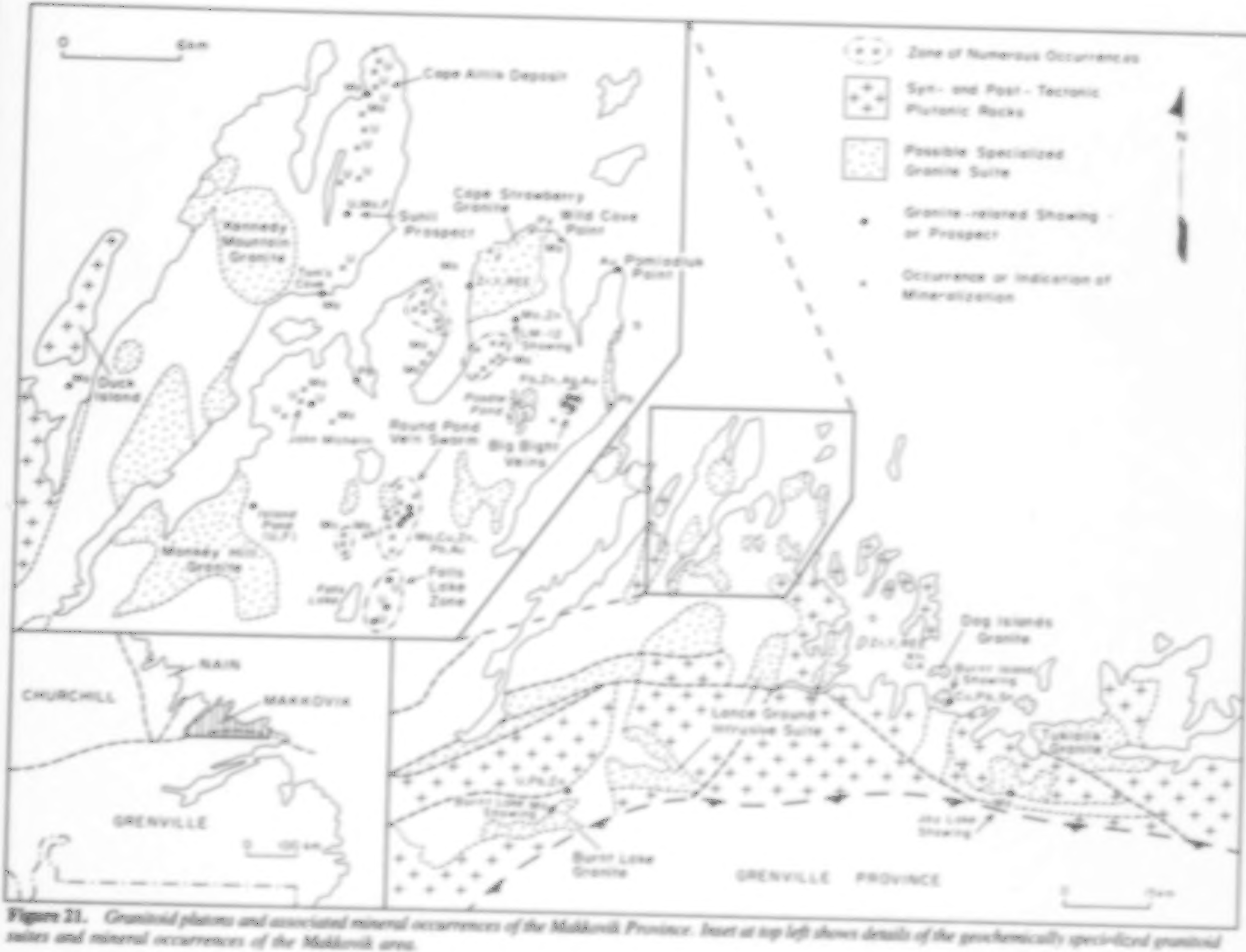

0
5km
Zone of Numerous Occurrences
Syn- and Post - Tectonic Plutonic Rocks
Possible Specialized Granite Suite
Granite-related Showing or Prospect
Occurrence or Indication of Mineralization
N
Cape Aillik Deposit
Sunil Prospect
Cape Strawberry Granite
Wild Cove Point
Pomiadluk Point
Kennedy Mountain Granite
Tom's Cove
Duck Island
Round Pond Vein Swarm
Big Bight Veins
Pistolet Pond
Monkey Hill Granite
Falls Lake Zone
Falls Lake
John Michelin
Dog Islands Granite
Burnt Island Showing
Lance Ground Intrusive Suite
Tukialik Granite
Burnt Lake Granite
Burnt Lake Mo Showing
Jim Lake Showing
GRENVILLE PROVINCE
NAIN
CHURCHILL
MAKKOVIK
GRENVILLE
0
100 km
0
10 km

Figure 21. *Granitoid plutons and associated mineral occurrences of the Makkovik Province. Inset at top left shows details of the geochemically specialized granitoid suites and mineral occurrences of the Makkovik area.*

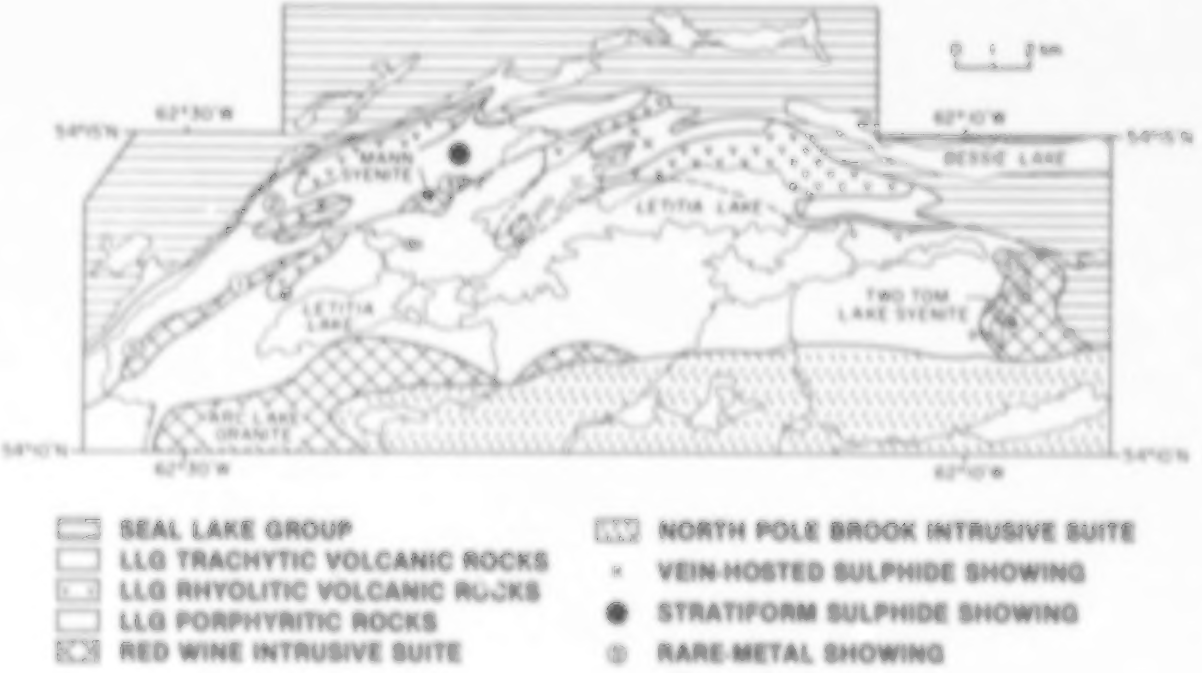

0 1 2 km
54°15'N
62°30'W
62°10'W
54°10'N
MANN SYENITE
LETITIA LAKE
DESSE LAKE
LETITIA LAKE
TWO TOM LAKE SYENITE
ARC LAKE GRANITE
SEAL LAKE GROUP
LLG TRACHYTIC VOLCANIC ROCKS
LLG RHYOLITIC VOLCANIC ROCKS
LLG PORPHYRITIC ROCKS
RED WINE INTRUSIVE SUITE
NORTH POLE BROOK INTRUSIVE SUITE
VEIN-HOSTED SULPHIDE SHOWING
STRATIFORM SULPHIDE SHOWING
RARE-METAL SHOWING

Figure 22. *Geology and mineral occurrences of the Letitia Lake Group.*

to medium-grained quartzofeldspathic gneiss of the Menihek Formation in the upper Knob Lake Group. These metasediments can be traced northeastward into Labrador, where there are a number of graphite showings (Figure 25). A geophysical and prospecting survey carried out in the Labrador City–Wabush area in 1989 by the Newfoundland Department of Mines and Energy (Meyer, 1990), rediscovered one of these showings, the Mart Lake graphite prospect. A 15-m-long trench on this prospect returned an average of 42 percent carbon, although the flake size is small and fine grinding would be required to achieve the desired purity level of 90 percent or greater. There are many significant untested conductors on this property, as well as relatively untested graphite prospects elsewhere in the area. Furthermore, there is a considerable exploration potential for undiscovered deposits.

A little-known and short-lived graphite mining operation was carried out near Saglek in northern Labrador during World War II (Carr, 1958). The 'lump' or vein-type' graphite is hosted by mylonitic Tasiuyak quartz–feldspar–garnet–graphite gneiss, and is thought to be similar to deposits mined in Sri Lanka. The 30- to 90-cm-thick lens that was mined, is exposed over 8 m (Meyer and Dean, 1988). Further occurrences of graphite have been reported in the same geological unit immediately north of the Fraser River (McConnell, 1984) and there would appear to be a considerable exploration potential for larger, more important deposits in the area (Douglas, 1953).

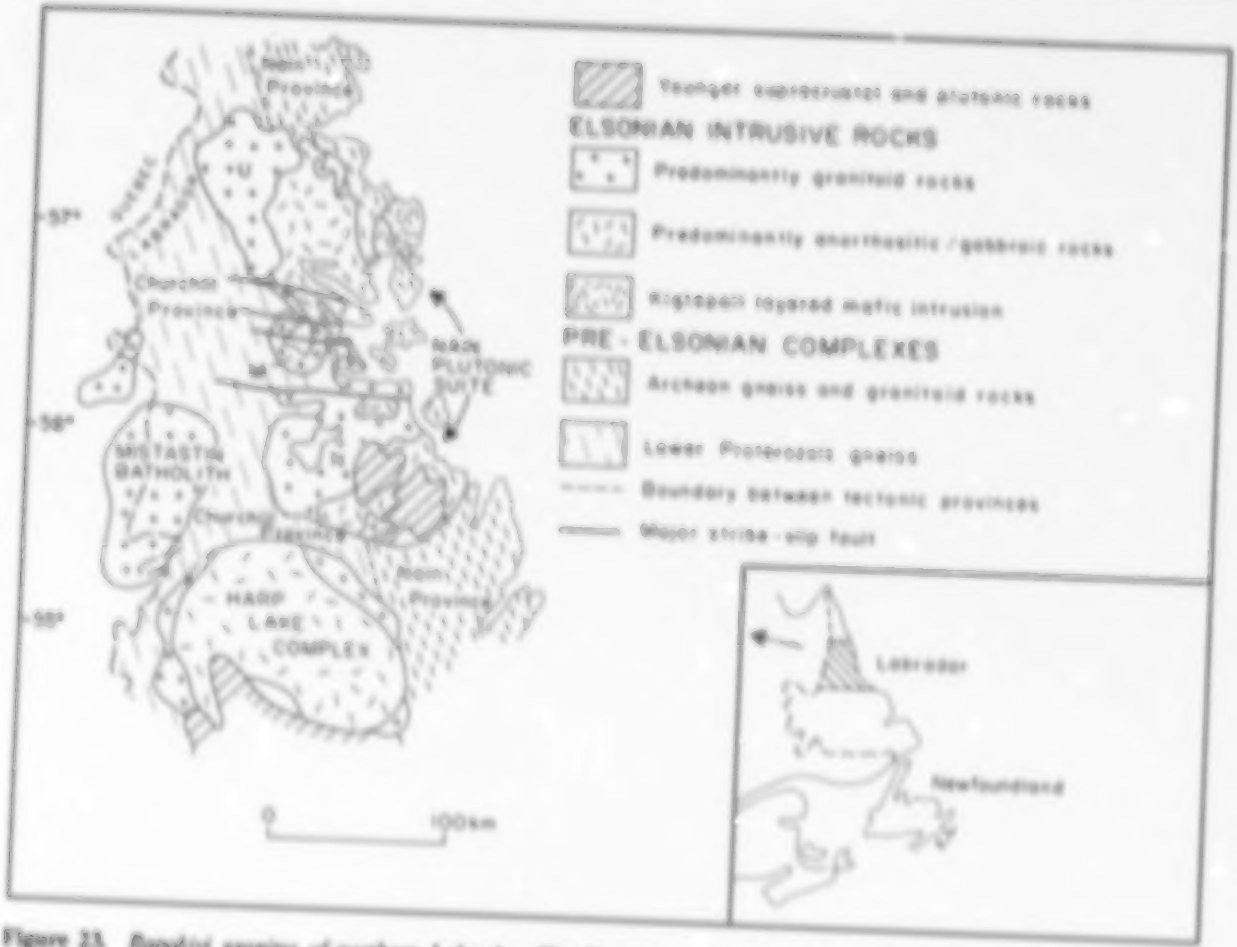
Refractory Minerals–Western Labrador

There are many kyanite–garnet–muscovite prospects in the Attikamagen Formation in the Labrador City–Wabush area (Figure 25). One of the best prospects occurs at the south end of Flora Lake (Rivers, 1978; Meyer and Dean, 1988) where kyanite–garnet–mica–quartz schists contain up to 20 percent kyanite, 10 to 20 percent garnet and 10 to 15 percent mica (dominantly muscovite). There is considerable potential for other high-grade deposits to be found in the area.

There is only one producer of kyanite in North America at the present time, and there is strong growth in garnet and muscovite markets (Metals Economics Group, 1988). Thus, there is good economic potential for one operation to produce these three industrial minerals.

Dimension Stone–North Labrador Coast

In 1986, the Department of Mines and Energy sampled three dimension-stone prospects in the Nain anorthosite, on the northern Labrador coast (Meyer and Dean, 1987). Recent interest by a major Italian stone company has focussed on one of these prospects at 10-Mile Bay, where a uniformly medium-grained, light-grey anorthosite, with up to 20 percent of the labradorite crystals showing flashes of blue on a cut surface, outcrops at tidewater. A 10-tonne block was quarried by the Labrador Inuit Development Corporation in the fall of 1990 and shipped to Italy. If tests on the anorthosite block are satisfactory, development of the deposit may follow.


Younger supracrustal and plutonic rocks
ELSONIAN INTRUSIVE ROCKS
Predominantly granitoid rocks
Predominantly anorthositic / gabbroic rocks
Kiglapait layered mafic intrusion
PRE - ELSONIAN COMPLEXES
Archean gneiss and granitoid rocks
Lower Proterozoic gneiss
Boundary between tectonic provinces
Major strike - slip fault
Nain Province
QUEBEC LABRADOR
Churchill Province
NAIN PLUTONIC SUITE
MISTASTIN BATHOLITH
Churchill Province
Nain Province
HARP LAKE COMPLEX
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M
N
57°
58°
56°
0
100km
Labrador
Newfoundland

Figure 23. *Rapakivi granites of northern Labrador. The Elsonian granitoid rocks of this area have some or all of the characteristics of the Rapakivi suite. U–Umiakovik; M–Makhavinekh; N–Notakwanon plutons.*

Anorthosite is widespread on the many islands and fiords of the north Labrador coast between Davis Inlet and the area north of Nain. The establishment of a dimension-stone quarry in the Nain area, and shipping of rough block to European processing plants, could open up the entire Labrador coast south of Nain for exploration.

Mica–Southeastern and Western Labrador

Muscovite-bearing pegmatites have been reported from the southeast Labrador coast (Gower *et al.*, 1986b, 1987), and from roadcuts in western Labrador (Meyer and Dean, 1988). One of the southern Labrador pegmatites is 10 m wide, has an exposed strike length of 50 m (Gower *et al.*, 1985), and contains free-splitting books of sheet muscovite up to 30 cm in diameter and 15 cm thick (Meyer, 1990). During regional mapping of the area, numerous other pegmatites were mapped by Gower *et al.* (1986b). The market for sheet muscovite is small, but prices range up to C$2000 per kilogram.

Ti-Sands–Lake Melville

Investigations into the heavy-mineral placer potential in the Lake Melville area and the coastal zone between Groswater Bay and Sandwich Bay, were carried out in 1990 (Emory-Moore and Meyer, *in preparation*). Numerous rivers entering these areas drain hinterlands underlain by gabbro–anorthosite massifs containing disseminated ilmenite. Black sand lenses and laminations are visible in the extensive postglacial deltaic, estuarine and littoral sands. Preliminary investigations suggest that the reworked postglacial sediments in modern beach environments exhibit the highest placer potential. The highest concentration of heavy minerals encountered during the sampling program occurred along a 20-km-long coastal-beach system north of Cartwright, with up to 50 percent heavy minerals over a 1 m thickness. Detailed mineralogical analyses are now underway to evaluate the potential for obtaining low-alkali TiO_2 concentrates from these deposits.

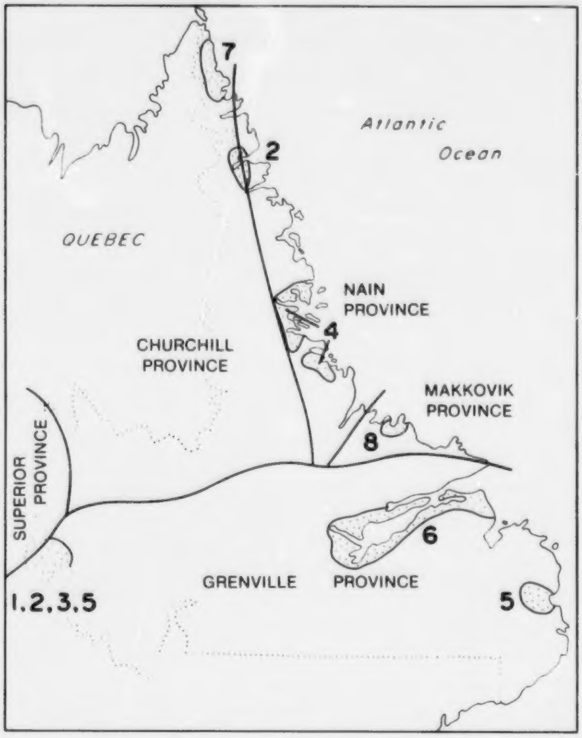

Figure 24. *Location of main industrial mineral prospects in Labrador. 1–silica; 2–graphite; 3–refractory minerals; 4–dimension stone; 5–mica; 6–Ti-rich sands; 7–chromite; 8–diamonds.*

Chromite–Northern Labrador

Podiform, sill-like anorthosites occur in the northern part of the Nain Province and are reflected in widespread Ni anomalies in stream sediments. These bodies, mapped by Taylor (1979), are believed to be Archean in age, as they are cut by early Proterozoic dykes (Wilton and Wardle, 1990), inviting a comparison with the mid-Archean Fiskenaesset Complex of western Greenland, a layered anorthosite intrusion that was dismembered by ca. 2.9 to 2.8 Ga magmatism and contains seams of chromite (Ghisler, 1976). Wilton and Wardle (1990) described examples of these anorthosites at Noodleook (Ekortiarsuk) Fiord and Eclipse Harbour. Although the presence of chromite was not confirmed in the field, subsequent laboratory studies (D. Phillips, personal communication, 1990) have recently found up to 1.2 percent Cr in ultramafic samples from Noodleook Fiord.

Diamond Potential–Labrador Coast

Various occurrences of alkaline mafic dykes are known from the Labrador coast. The most extensive development occurs in the Aillik Bay area of the Makkovik Province (Foley, 1989) where alkaline–ultramafic lamprophyres form a system of cone sheets and radial dykes thought to be related to an intrusive centre under the Labrador Sea. Lamprophyric dykes are thought to have formed ca. 0.6 to 0.57 Ga, in association with the St. Lawrence rift system, whereas the ultramafic lamprophyres and carbonatites are more likely Cretaceous (Foley, 1989). Small kimberlite–alnöite pipes and dykes also occur in the Saglek area of the northern Nain Province (Collerson and Malpas, 1977) and also are likely of Cretaceous age and related to opening of the Labrador Sea. The kimberlitic affinity of these various alkaline rocks suggests that they may be worth prospecting for their diamond potential.

CONCLUSIONS

The exploration environments that have been highlighted briefly in this paper represent some of the grassroots targets that Labrador has to offer. Our presentation of the mineral potential of this area is, to some extent, coloured by the state of our knowledge (e.g., the graphite potential of western Labrador has been given a significant boost by the recent Lac Knife discovery) and by the market interest in various commodities (i.e., although we have not emphasized the uranium potential, there are a number of prospective environments that could be quickly identified if there were renewed interest in uranium exploration). As geological mapping and related regional studies continue in this area, new targets will undoubtedly be identified and a better focus for exploration related to known targets will be achieved.

Exploration in Labrador has traditionally suffered from the remoteness of the country and from a perception (in part based on inadequate geological information) that there are no prospective environments. In fact, the environments are there and the lack of major non-ferrous mineral deposits in Labrador may be largely a function of the lack of modern exploration. There is considerable potential for a variety of deposit types related to lower grade rocks (e.g., the Central Mineral Belt, eastern Labrador granitoid rocks) in which current deposit models could be applied in a relatively straightforward manner. Although it is true that much of Labrador is at relatively high metamorphic grades, making the application of some deposit models more speculative, some deposit types actually require high-grade metamorphism (e.g., refractories, graphite) and pre-metamorphic deposits that might occur in these areas (e.g., Besshi-type or SEDEX deposits) could have survived the variably intense deformation and metamorphism more or less intact. Although exploration for these deposits using geological models will certainly be more difficult in relatively high-grade, deformed terranes, it seems likely that, as the easily found large deposits in lower grade terranes are all discovered, exploration will need to be focused in the more geologically difficult regions. Armed with new geological concepts and remote sensing techniques, and the need to meet an ever increasing demand for metals from ever decreasing resources, it may well be that explorationists will find a minerals storehouse in Labrador that will provide important resources for the province well into the 21st century.

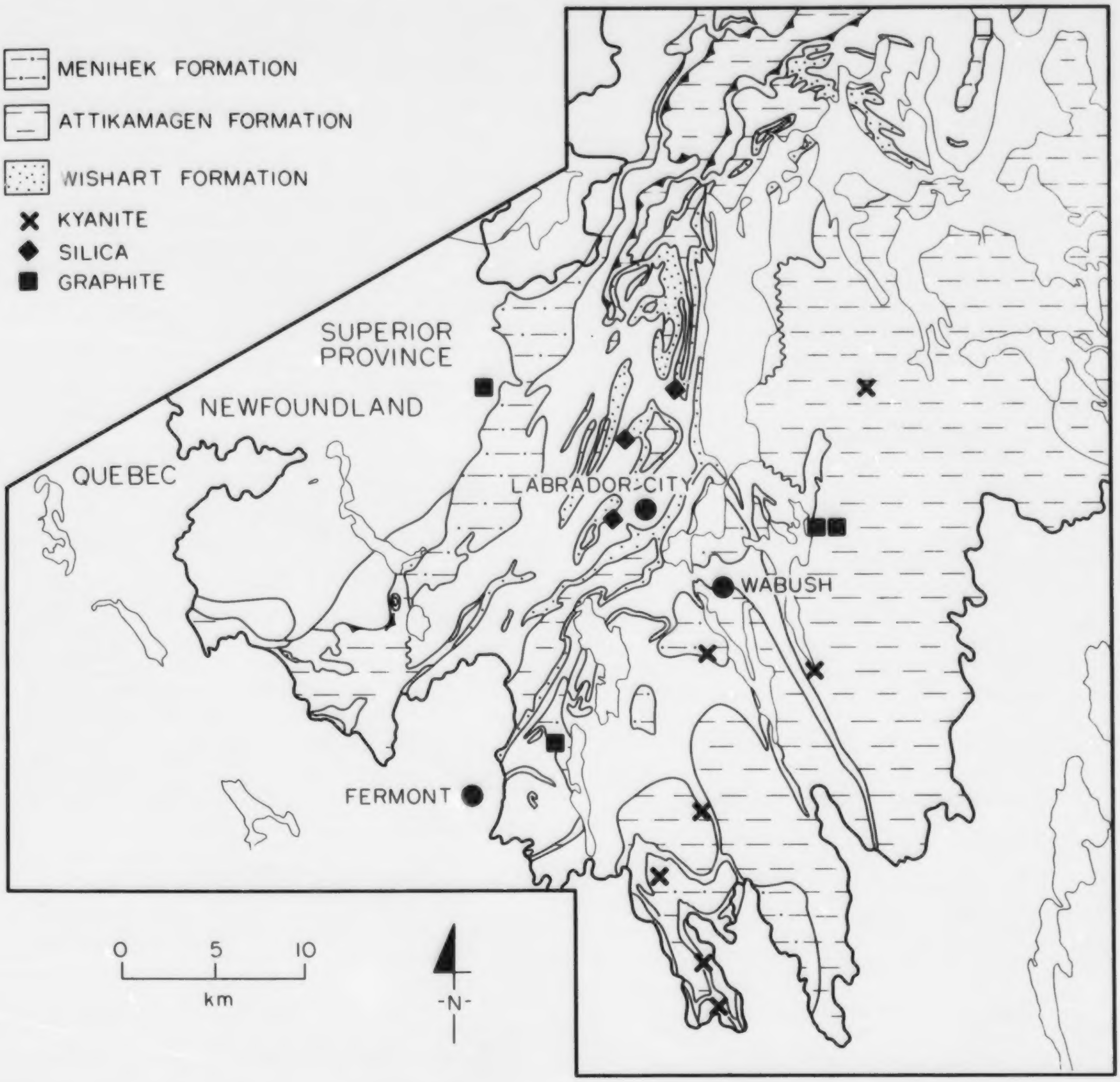
MENIHEK FORMATION
ATTIKAMAGEN FORMATION
WISHART FORMATION
KYANITE
SILICA
GRAPHITE
SUPERIOR PROVINCE
NEWFOUNDLAND
QUEBEC
LABRADOR CITY
WABUSH
FERMONT
0
5
10
km
N

Figure 25. *Industrial minerals in western Labrador and distribution of geological units with further industrial-minerals potential.*

REFERENCES

Aberg, G.
1988: Middle Proterozoic anorogenic magmatism in Sweden and worldwide. Lithos, Volume 21, pages 279-289.

Appel, P.W.U.
1988: On an Sn-W bearing iron formation in the Archean Malene supracrustals, West Greenland. Precambrian Research, Volume 39, pages 131-137.

Bailey, D.G.
1979: Geology of the Walker–MacLean Lake area, (13K/9E, 13J/12), Central Mineral Belt, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-3, 17 pages.

Barley, M.E. and Groves, D.I.
1990: Mesothermal fold mineralization in the Yilgarn Craton, Western Australia, the result of late Archean convergent tectonics? Chronique de la Recherche Miniere, Volume 496, pages 3-13.

Baragar, W.R.A.
1967: Wakuach Lake map-area. Geological Survey of Canada, Memoir 344, 174 pages.

Batterson, M.J.
1989a: Glacial dispersion from the Strange Lake alkalic complex, northern Labrador. *In* Drift Prospecting. *Edited by* R.N.W. DiLabio and W.B. Coker. Geological Survey of Canada, Paper 89-20, pages 31-40.

1989b: Quaternary geology and glacial dispersion in the Strange Lake area, Labrador. Newfoundland Department of Mines and Energy, Geological Survey Branch, Paper 89-3, 51 pages.

Beavan, A.P.
1958: The Labrador uranium area. Proceedings of the Geological Association of Canada, Volume 10, pages 137-145.

Berg, J.H.
1983: Stratigraphic comparison of the Snyder and Falls Brook Groups with the Mugford Group. *In* The Nain Anorthosite Project, Labrador: Field Report 1981. *Edited by* S.A. Morse. Department of Geology and Geography, University of Massachusetts, Contribution 40, pages 16-22.

Bickford, M.E., Van Schmus, W.R. and Zietz, I.
1986: Proterozoic history of the midcontinent region of North America. Geology, Volume 14, pages 492-496.

Böhmke, F.C. and Varndell, B.J.
1986: Gold in granulites at Renco mine, Zimbabwe. *In* Mineral Deposits of Southern Africa (Volume I). *Edited by* C.R. Anheusser and S. Maske. Geological Society of South Africa, Special Publication, pages 221-230.

Brace, T.D.
1991: Geology, geochemistry and metallogeny of the Archean Florence Lake Group and associated ultramafic and trondhjemitic rocks, southern Nain Province, central Labrador. Unpublished M.Sc. Thesis, Memorial University of Newfoundland, St. John's, 271 pages.

Brace, T.D. and Wilton, D.H.C.
1990. Platinum group elements (PGE) in the Archean Florence Lake Group, central Labrador. Canadian Mineralogist, Volume 28, pages 419-430.

Bridgwater, D., Collerson, K.D. and Myers, J.S.
1978: The development of the Archean gneiss complex of the North Atlantic region. *In* Evolution of the Earth's Crust. *Edited by* D.H. Tarling, London, Academic Press, pages 19-69.

Bridgwater, D., Escher, A. and Watterson, J.
1973: Tectonic displacements and thermal activity in two contrasting Proterozoic mobile belts from Greenland. Philosophical Transactions of the Royal Society of London, Volume A273, pages 513-533.

Brummer, J.J.
1960: A reconnaissance geochemical survey in the Seal Lake area, Labrador. Canadian Mining and Metallurgical Bulletin, Volume 63, pages 1-8.

Brummer, J.J. and Mann, E.L.
1961: Geology of the Seal Lake area, Labrador. Geological Society of America Bulletin, Volume 72, pages 1361-1382.

Butler, J.
1987: Detailed lake sediment surveys in western Labrador for gold and associated elements. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Lab. 716, 16 pages.

Carr, G.F.
1958: The industrial minerals of Newfoundland. Department of Mines and Technical Surveys, Industrial Minerals Division, Mines Branch, No. 855, 158 pages.

Collerson, K.D. and Malpas, J.G.
1977: Partial melts in upper mantle nodules from Labrador Kimberlites. Second International Kimberlite Conference, Extended Abstracts (unpaginaged).

Collerson, K.D., Jesseau, C.W. and Bridgwater, D.
1976: Crustal development of the Archean gneiss complex, eastern Labrador. *In* The Early History of the Earth. *Edited by* B.F. Windley. Wiley Interscience Publications, pages 237-253.

Currie, K.L.
1985: An unusual peralkaline granite near Lac Brisson, Quebec-Labrador. *In* Current Research, Part A. Geological Survey of Canada, Paper 85-1A, pages 73-80.

Davenport, P.H. and Nolan, L.W.
1989: Mapping the distribution of gold in Newfoundland using lake sediment geochemistry. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 259-266.

Dean, P.L. and Meyer, J.R.
1985: Industrial minerals in Labrador West. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 1-3.

Dimroth, E., Baragar, W.R.A., Bergeron, R and Jackson, G.D.
1970: The filling of the Circum–Ungava Geosyncline. *In* Basins and Geosynclines of the Canadian Shield. *Edited by* A.J. Baer. Geological Survey of Canada, Paper 70-40, pages 45-142.

Douglas, G.V.
1953: Notes on localities visited on the Labrador coast in 1946 and 1947. Geological Survey of Canada, Paper 53-1, 67 pages.

Einsele, G.
1986: Interaction between sediments and basalt injections in young Gulf of California-type spreading centers. Geologische Rundschau, Volume 75, pages 197-208.

Eisenlohr, B.N., Groves, D.I. and Partington, G.A.
1989: Crustal scale shear zones and their significance to Archean gold mineralization. Mineralium Deposita, Volume 24, pages 1-8.

Elston, E.W., Rhodes, R.C. and Erb, E.E.
1976: Control of mineralization by mid-Tertiary volcanic centers, southwestern New Mexico. *In* Cenozoic Volcanism in Southwestern New Mexico. *Edited by* E.W. Elston and S.A. Northrop. New Mexico Geological Society, Special Publication 5, pages 125-130.

Emory-Moore and Meyer, J.
In preparation: Origin and economic potential of placer deposits in the Lake Melville and Porcupine Strand area of eastern Labrador.

Emslie, R.F.
1970: The geology of the Michikamau Intrusion, Labrador (13L, 23I). Geological Survey of Canada, Paper 68-57, 85 pages.

1978: Anorthosite massifs, rapakivi granites, and late Proterozoic rifting of North America. Precambrian Research, Volume 7, pages 61-98.

Ermanovics, I.F. and Korstgaard, J.A.
1981: Geology of Hopedale Block and adjacent areas, Labrador: Report 3. *In* Current Research. Geological Survey of Canada, Paper 81-1A, pages 69-76.

Ermanovics, I.F., Korstgaard, J.A. and Bridgwater, D.
1982: Structural and lithological chronology of the Archean Hopedale block and adjacent Makkovik Subprovince, Labrador. Geological Survey of Canada, Paper 82-1B, pages 153-165.

Evans, D.T.W.
This volume: Gold metallogeny, eastern Dunnage Zone, central Newfoundland.

Evans, E.L.
1952: Native copper discoveries in the Seal Lake area, Labrador. Proceedings of the Geological Association of Canada, Volume 5, pages 111-116.

Fenco-Lavalin
1988: Prefeasibility study of the establishment of a silica-based industry in Labrador West. Unpublished report to the Newfoundland Department of Mines and Energy and Energy, Mines and Resources, Canada. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File Lab 783, 70 pages.

Findlay, J.M., Fowler, A.D. and Birkett, T.C.
1988: Platinum group element potential of the Howse Lake area, western Labrador. Newfoundland Department of Mines, Geological Survey Branch, Open File 23O(29).

Foley, S.F.
1989: Emplacement features of lamprophyre and carbonatitic lamprophyre dykes at Aillik Bay, Labrador. Geological Magazine, Volume 126, pages 29-42.

Gaal, G. and Gorbatschev, R.
1987: An outline of the Precambrian evolution of the Baltic Shield. Precambrian Research, Volume 35, pages 15-52.

Gandhi, S.S.
1976: Geological setting and genetic aspects of uranium occurrences in the Kaipokok Bay–Big River area, Labrador. Economic Geology, Volume 73, pages 1492-1522.

1978: Geological setting and genetic aspects of uranium occurrences in the Kaipokok Bay–Big River area, Labrador. Economic Geology, Volume 73, pages 1492-1523.

Gandhi, S.S. and Brown, A.C.
1975: Cupriferous shales of the Adeline Island Formation, Seal Lake Group, Labrador. Economic Geology, Volume 70, pages 145-163.

Gandhi, S.S., Krogh, T.E. and Corfu, F.
1988: U–Pb zircon and titanite dates on two granitic intrusions of the Makkovik Orogen and a peralkaline granite of the Red Wine Intrusive Complex, central Labrador. Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists, Joint Annual Meeting, St. John's, Program with Abstracts, Volume 13, page A42.

Geological Survey of Canada
1979: Regional lake sediment and water geochemical reconnaissance data, Labrador, 1978. Geological Survey of Canada, Open File 560.

1982a: Regional lake sediment and water geochemistry reconnaissance data, NTS 23G, Labrador. Geological Survey of Canada, Open File 903.

1982b: Regional lake sediment and water geochemistry reconnaissance data, NTS 23J, Labrador. Geological Survey of Canada, Open File 904.

Ghisler, M.
1976: The geology, mineralogy and geochemistry of the Pre-orogenic Archean stratiform chromite deposits at Fiskenaesset, West Greenland. Monograph Series on Mineral Deposits No. 14, Gebruder Bomtraeger, Berlin, 156 pages.

Gower, C.F.
1990: Mid-Proterozoic evolution of the eastern Grenville Province, Canada. Geologiska Föreningens i Stockholm Förhandlingar, Volume 122, pages 127-139.

Gower, C.F. and Erdmer, P.
1984: The mineral potential of paragneiss in the Grenville Province in eastern Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-1, pages 80-87.

Gower, C.F., Erdmer, P. and Wardle, R.J.
1986a: The Double Mer Formation and the Lake Melville rift system, eastern Labrador. Canadian Journal of Earth Sciences, Volume 23, pages 359-368.

Gower C.F., Flanagan, M.J., Kerr, A. and Bailey, D.G.
1982: The geology of the Kaipokok Bay–Big River area, Central Mineral Belt, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-7, 77 pages.

Gower, C.F., Heaman, L.M., Loveridge, W.D., Schärer, U. and Tucker, R.D.
In press,b: Grenvillian granitoid plutonism in the eastern Grenville Province, Canada. Precambrian Research.

Gower, C.F. and Loveridge, W.D.
1987: Grenvillian plutonism in the eastern Grenville Province. *In* Radiogenic Age and Isotope Studies: Report 1. Geological Survey of Canada, Report 87-2, pages 55-58.

Gower, C.F., Neuland, S., Newman, M. and Smyth, J.
1986b: Geology of the Sand Hill River–Batteau map region, Grenville Province, eastern Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 101-111.

1987: Geology of the Port Hope Simpson map region, Grenville Province, eastern Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 183-199.

Gower, C.F., Noel, N. and van Nostrand, T.
1985: Geology of the Paradise River region, Grenville Province. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 19-32.

Gower, C.F. and Owen, V.
1984: Pre-Grenvillian and Grenvillian lithotectonic regions in eastern Labrador–correlations with the Sveconorwegian Orogenic Belt in Sweden. Canadian Journal of Earth Sciences, Volume 21, pages 678-693.

Gower, C.F. and Ryan, B.
1986: Proterozoic evolution of the Grenville Province and adjacent Makkovik Province in eastern-central Labrador. *In* The Grenville Province. *Edited by* J.M. Moore, A. Davidson and A.J. Baer. Geological Association of Canada, Special Paper 31, pages 281-296.

Gower, C.F., Ryan, A.B. and Rivers, T.
In press,a: Mid-Proterozoic Laurentia-Baltica: an overview of its geological evolution and a summary of the contributions made by this volume. *In* Mid-Proterozoic Laurentia-Baltica. *Edited by* C.F. Gower, T. Rivers and A.B. Ryan. Geological Association of Canada, Special Paper 38.

Gower, C.F. and Swinden, H.S.
This volume: Pillow lavas in the Dead Islands area, Grenville Province, Labrador.

Gower, C.F., van Nostrand, T. and Smyth, J.
1988: Geology of the St. Lewis River map region, Grenville Province, eastern Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 59-73.

Greene, B.A.
1972: Geological map of Labrador. Newfoundland Department of Mines, Agriculture and Resources, Mineral Resources Division.

Gross, G.A.
1968: Geology of Iron Deposits in Canada, Volume III, Iron Ranges of the Labrador Geosyncline. Geological Survey of Canada, Economic Geology Report 22, 179 pages.

Haapala, I.
1988: Metallogeny of the Proterozoic rapakivi granites of Finland. *In* Recent Advances in the Geology of Granite-related Mineral Deposits. *Edited by* R.P. Taylor and D.F. Strong. Canadian Institute of Mining and Metallurgy, Special Volume 39, pages 124-132.

Hill, J.D.
1982: Geology of the Flowers River area, Labrador: Newfoundland Department of Mines and Energy, Mineral Development Division, Report 81-6, 40 pages.

Hill, J.D. and Thomas, A.
1983: Correlation of two Helikian peralkaline granite-volcanic centres in central Labrador. Canadian Journal of Earth Sciences, Volume 20, pages 753-763.

Hill, J.D. and Miller, R.R.
In press: A review of early Neohelikian epigenetic felsic magmatism in Labrador. *In* Mid-Proterozoic Laurentia-Baltica. *Edited by* C.F. Gower, T. Rivers and B. Ryan. Geological Association of Canada, Special Paper 38.

Hoffman, P.F.
1987: Early Proterozoic foredeeps, foredeep magmatism and Superior-type iron formation of the Canadian shield. *In* Proterozoic Lithospheric Evolution. *Edited by* A. Kröner. Geodynamic Series, Volume 17, Washington, D.C., American Geophysical Union, pages 85-98.

1988: United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. Annual Review of Earth and Planetary Sciences, No. 16, pages 543-603.

1989: Precambrian geology and tectonic history of North America. *In* The Geology of North America: an overview. *Edited by* A.W. Bally and A.R. Palmer. Geological Society of America, Decade of North American Geology Summary Volume A, Chapter 16, pages 447-512.

Hornbrook, E.H.W. and Friske, P.W.B.
1988a: National geochemical reconnaissance lake sediment and water geochemical data, eastern Labrador (parts of 13I, 13J, 13K, 13N and 13O). Geological Survey of Canada, Open File 1636.

1988b: Regional stream and lake sediment and water geochemical infill survey data, eastern Labrador. Geological Survey of Canada, Open File 1637.

1989: National geochemical reconnaissance lake sediment and water geochemical data, west-central Labrador (parts of 23I, 23J and 23O). Geological Survey of Canada, Open File 2037.

Jesseau, C.W.
1976: A structural—metamorphic and geochemical study of the Hunt River supracrustal belt, Nain Province, Labrador. Unpublished M.Sc. Thesis, Memorial University of Newfoundland, St. John's, 211 pages.

Kamo, S.L., Gower, C.F. and Krogh, T.E.
1989: Birthdate for the Iapetus Ocean? Geology, Volume 17, pages 602-605.

Kerr, A.
1987: Plutonic rocks of the eastern Central Mineral Belt: lithogeochemical patterns and identification of potential specialized granitoids. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 161-181.

1988: Geochemical characteristics and mineral potential of specialized granitoid plutons in the Trans-Labrador batholith, eastern Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 15-36.

1989: Early Proterozoic granitoid magmatism and crustal evolution in the Makkovik Province of Labrador: A geochemical and isotopic study. Unpublished Ph.D. Thesis, Memorial University of Newfoundland, St.John's, 528 pages.

In preparation: Geology, geochemistry and mineral potential of plutonic rocks in the eastern part of the Central Mineral Belt, Labrador. Newfoundland Department of Mines and Energy, Geological Survey Branch Report.

Kerr, A. and Davenport, P.A.
In press: Application of geochemical mapping techniques to a complex Precambrian shield area, in Labrador, Canada. Journal of Geochemical Exploration.

Kerr, A. and Fryer, B.J.
In press: Sources of Early Proterozoic magmas in the Makkovik Province of eastern Labrador: Evidence from Nd isotope data. *In* Mid-Proterozoic Laurentia-Baltic. *Edited by* C.F. Gower, T. Rivers and B. Ryan. Geological Association of Canada, Special Paper 38.

Kerr, A. and Krogh T.E.
1990: The Trans-Labrador Granitoid Belt in the Makkovik Province: new geochronological and isotopic data and their geological implications. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 90-1, pages 237-249.

Kerrich, R.
1989: Geodynamic setting and hydraulic regimes: shear hosted mesothermal gold deposits. *In* Mineralization and Shear Zones. *Edited by* J. Bursnall. Geological Association of Canada, Short Course Notes, Volume 6, pages 89-128.

Kisvarsanyi, E.B.
1988: Buried Proterozoic Terranes in the Midcontinent; frontiers for geological exploration. Process Mineralogy VII, The Metallurgical Society Inc., Warrendale, Pennsylvania, pages 315-326.

Korstgaard, J. and Ermanovics, I.F.
1985: Tectonic evolution of the Archean Hopedale Block and the adjacent Makkovik Subprovince, Labrador, Newfoundland. *In* Evolution of Archean Supracrustal Sequences. *Edited by* L.D. Ayres, P.C. Thurston, K.D. Card and W. Weber. Geological Association of Canada, Special Paper 28, pages 223-237.

Korstgaard, J., Ryan, B. and Wardle, R.
1987: The boundary between Proterozoic and Archaean crustal blocks in central West Greenland and northern Labrador. *In* Evolution of the Lewisian and Comparable Precambrian High Grade Terranes. *Edited by* R.G. Park and J. Tarney. Geological Society Special Publication 27, pages 247-259.

Knight, I. and Morgan, W.C.
1981: The Aphebian Ramah Group. *In* Proterozoic Basins of Canada. *Edited by* F.H.A. Campbell. Geological Survey of Canada, Paper 81-10, pages 313-330.

Lapointe, B.
1986: Reconnaissance géologique de la région du lac Pailleraut, Territoire du Nouveau Québec. Ministere de l'Energie et des Ressources, Gouvernement du Québec, MB85-73, 11 pages.

Lindh, A.
1990: The Scandinavian Grenville–the Southwest Scandinavian Gneiss Complex: Field Excursion 3. A traverse north of Lake Vänern. Second symposium on the Baltic Shield, 27 pages.

MacDougall, C.S.
1988: A metallogenic study of polymetallic granophile mineralization within the Early Proterozoic Upper Aillik Group, Round Pond area, Central Mineral Belt, Labrador. Unpublished M.Sc. Thesis, Memorial University of Newfoundland, St. John's, 245 pages.

MacDougall, C.S. and Wilton, D.H.C.
1987a: Middle Proterozoic granite-related mineralization in the Round Pond area, Labrador. *In* Current Research. Geological Survey of Canada, Report 87-1A, pages 457-466.

1987b: A new showing with associated precious metals, in the Round Pond area, near Makkovik, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Report 13O/3(110), 9 pages.

MacKenzie, L.M. and Wilton, D.H.C.
1987: Uranium, molybdenum and base metal sulphide mineralization in the Burnt Lake area, central Labrador; three different styles of ore formation. *In* Current Research. Geological Survey of Canada, Report 87-1A, pages 467-477.

MacLeod, J.L.
1984: First year assessment report on geological and geochemical exploration for Licences 100R–101R on property in the Ramah Bay area, Labrador. Unpublished report to ESSO Minerals Canada Ltd. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File 014L/0037.

1985: First year assessment report on geological and geochemical exploration for the SMS Project for Licenses 100R–101R on property in the Saglek Fiord and Delabarre Bay areas, Labrador. Unpublished report to ESSO Minerals Canada Ltd. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File 014L/0038.

Marten, B.E.
1975: Geology of the Letitia Lake area, Labrador. *In* Report of Activities. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 75-1, pages 75-86.

McConnell, J.W.
1984: Reconnaissance and detailed geochemical surveys for base metals in Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-2, 114 pages.

1988: Lake sediment and water geochemical surveys for rare-metal mineralization in granitoid terranes in Churchill province, Labrador. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File Lab 772, 100 pages.

1989: Lake sediment and water geochemical surveys for rare-metal mineralization in Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 267-278.

McConnell, J.W. and Batterson, M.J.
1987: The Strange Lake Zr–Y–Nb–Be–REE Deposit, Labrador: A geochemical profile in till, lake and stream sediment, and water. Journal of Geochemical Exploration, Volume 29, pages 105-127.

McConnell, J.W. and Newman, L.A.
1988: Surficial geochemical surveys of auriferous portions of the Ashuanipi Complex, western Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 397-401.

Metals Economics Group
1988: A study of U.S. East Coast Industrial Minerals markets for New Brunswick, Newfoundland and Nova Scotia. Unpublished report for Energy, Mines and Resources, Canada. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File Nfld 1694.

Meyer, J.R.
1990: Graphite, muscovite and heavy-mineral sands exploration in Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 163-169.

Meyer, J.R. and Dean, P.L.
1986: Industrial minerals in Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 1-8.

1987: Silica in western Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 71-75.

1988: Industrial minerals and follow-up of lake- and stream-sediment geochemical anomalies in Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 247-259.

Miller, R.R.
1988: Yttrium (Y) and other rare metals (Be, Nb, REE, Ta, Zr) in Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 229-246.

Mitchell, A.H.G. and Bell, J.D.
1973: Island-arc evolution and related mineral deposits. Journal of Geology, Volume 81, pages 381-405.

Morgan, W.C.
1975: Geology of the Precambrian Ramah Group and basement rocks in the Nachvak Fiord–Saglek Fiord area, north Labrador. Geological Survey of Canada, Paper 74-54, 42 pages.

Morse, S.A.
1969: The Kiglapait Layered Intrusion, Labrador. Geological Society of America, Memoir 112, 204 pages.

1980: Kiglapait Mineralogy II: Fe–Ti oxide minerals and the activities of oxygen and silica. Journal of Petrology, Volume 21, pages 685-719.

Mortenson, J.K. and Percival, J.A.
1987: Reconnaissance U–Pb zircon and monazite geochronology of the Lac Clairambault area, Ashuanipi Complex, Quebec. *In* Radiogenic Age and Isotopic Studies: Report 1. Geological Survey of Canada, Paper 87-2, pages 135-142.

Neilsen, T.D.F. and Schønwandt, H.K.
1990: Gold and platinum group metal mineralization in the Skaergaard intrusion, southern East Greenland. *In* Current Research, including Report of Activities, 1989. Grønlands Geologiske Undersøgelse, Report 148, pages 101-103.

North, J.
1988: The stratigraphy, structure, geochemistry and metallogeny of the Moran Lake Group, Central Mineral Belt, Labrador. Unpublished M.Sc. Thesis, Memorial University of Newfoundland, St. John's, 202 pages.

North, J. and Wilton, D.H.C.
1988: Stratigraphy of the Warren Creek Formation, Moran Lake Group, Labrador Central Mineral Belt. *In* Current Research, Part C. Geological Survey of Canada, Report 88-1C, pages 123-128.

Nunn, G.A.G. and Noel, N.
1982: Regional geology east of Michikamau Lake, central Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 81-1, pages 149-167.

Nunn, G.A.G., Thomas, A. and Krogh, T.E.
1985: The Labradorian Orogeny: geochronological database. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, pages 43-54.

Nunn, G.A.G., Heaman, L.M. and Krogh, T.E.
In press: U–Pb geochronological evidence for Archean crust in the continuation of the Rae Province (Eastern Churchill Province), Grenville Front Tectonic Zone, Labrador. Geoscience Canada, pages 259-265.

Parr, J. and Rickard, D.
1987: Early Proterozoic subaerial volcanism and its relationship to Broken Hill-type mineralization in central Sweden. Geological Society of London, Special Publication 33, pages 81-93.

Percival, J.A.
1987: Geology of the Ashuanipi granulite complex in the Schefferville area, Quebec. *In* Current Research, Part A. Geological Survey of Canada, Paper 87-1A, pages 1-10.

Pharoah, T.C. and Pearce, J.A.
1984: Geochemical evidence for the geotectonic setting of early Proterozoic metavolcanic sequences in Lappland. Precambrian Research, Volume 25, pages 283-308.

Rivers, T.
1978: Geological mapping of the Wabush–Labrador City area, southwestern Labrador. *In* Report of Activities. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-1, pages 44-50.

Rämö, T. and Haapala, I.
In press: The rapakivi granites of eastern Fennoscandia: a review with insights into their origin in the light of new Sn–Nd isotopic data. *In* Mid-Proterozoic Laurentia-Baltica. *Edited by* C.F. Gower, T. Rivers and B. Ryan. Geological Association of Canada, Special Paper 38.

Ryan, B.
1977: Molybdenite: some background information, and a review of mineralization on the Aillik Peninsula, Labrador. Unpublished report, Newfoundland Department of Mines and Energy, Geological Survey Branch [13O/3(74)], 15 pages.

1984: Regional geology of the central part of the Central Mineral Belt, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Memoir 3, 185 pages.

In press: Makhavinekh Lake pluton, Labrador, Canada: geological setting, subdivisions, mode of emplacement, and a comparison with Finnish rapakivi granites. Precambrian Research.

Schärer, U., Krogh, T.E, Wardle, R.J., Ryan, B. and Gandhi, S.S.
1988: U-Pb ages of Early and Middle Proterozoic volcanism and metamorphism in the Makkovik Orogen Labrador. Canadian Journal of Earth Sciences, Volume 25, pages 1098-1107.

Sigmond, E.M.O.
1985: The Mandal–Ustaoset line, a newly discovered major fault zone in south Norway. *In* The Deep Proterozoic Crust in the North Atlantic Provinces. *Edited by* A.C. Tobi and J.L.R. Tourat. NATO Advanced Science Institute Series, Volume 158, pages 323-331.

Sillitoe, R.H.
1976: Metallic mineralization affiliated to subaerial volcanism: a review. *In* Volcanic Processes and Ore Genesis. Geological Society of London and the Institution of Mining and Metallurgy, Special Publication 7, pages 99-116.

Sims, P.K., Kisvarsanyi, E.B. and Morey, G.B.
1987: Geology and metallogeny of Archean and Proterozoic basement terranes in the northern midcontinent U.S.A.: An overview. United States Geological Survey, Bulletin 1815, 51 pages.

Slack, J.F. and Shanks, W.C. III
1989: Geologic and isotopic characteristics of modern and ancient Besshi-type massive sulfide deposits. 28th International Geological Congress, Washington, D.C., Abstracts, Volume 3, page 3-132.

Smith, D.R.
1968: Follow up of radio-active anomalies; Barringer areas 'A'–'J' Seal Lake, Labrador. Unpublished report for British Newfoundland Exploration Ltd. Newfoundland Department of Mines and Energy, Geological Survey Branch. [Lab (196)]

Smyth, W.R. and Knight, I.
1978: Correlation of the Aphebian supracrustal sequences, Nain Province, Northern Labrador. *In* Report of Activities for 1977. Newfoundland Department of Mines and Energy, Mineral Development Division, pages 59-64.

Smyth W.R., Marten, B.E. and Ryan, A.B.
1974: Geological mapping in the Central Mineral Belt, Labrador: redefinition of the Croteau Group. *In* Report of Activities. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 75-1, pages 51-74.

Speer, J.A.
1978: The stratigraphy and depositional environment of the Aphebian Snyder Group, Labrador. Canadian Journal of Earth Sciences, Volume 15, pages 52-68.

Stubbins, J.B., Blais, R.A. and Zajac, I.S.
1961: Origin of the soft iron ores of the Knob Lake Range. Transactions of the Canadian Institute of Mining and Metallurgy, Volume 64, pages 37-52.

Sutton, J.S., Marten, B.E., Clark, A.M.S. and Knight, I.
1972: Correlation of the Precambrian supracrustal rocks of coastal Labrador and southwestern Greenland. Nature, Physical Science, Volume 238, pages 122-123.

Thomas, A. and Butler, J.
1987: Gold reconnaissance in the Archean Ashuanipi Complex of western Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 237-255.

Tallman, P.
1990: Exploration results from the 'Hunan' antimony discovery in central Newfoundland. Canadian Institute of Mining and Metallurgy Bulletin, Volume 83, number 941, page 31.

Taylor, F.C.
1979: Reconnaissance geology of a part of the Precambrian Shield in northeastern Quebec, northern Labrador and Northwest Territories. Geological Survey of Canada, Memoir 393, 99 pages.

Tucker, R.D. and Gower, C.F.
1990: Salient features of the Pinware Terrane, Grenville Province, eastern Labrador. Geological Association of Canada, Program with Abstracts, Volume 15, page A133.

Van Kranendonk, M.J.
1990: Structural history and geotectonic evolution of the eastern Torngat Orogen in the North River map area, Labrador. *In* Current Research, Part C. Geological Survey of Canada, Paper 90-1C, pages 81-96.

Van Schmus, W.R. and Bickford, M.E.
1981: Proterozoic chronology and evolution of the midcontinent region, North America. *In* Precambrian Plate Tectonics. *Edited by* A. Kröner. Elsevier, Amsterdam, pages 261-296.

Vivallo, W. and Rickard, D.
1990: Genesis of an Early Proterozoic zinc deposit in a high-grade metamorphic terrane, Saxberget, central Sweden. Economic Geology, Volume 85, pages 714-736.

Wardle, R.J.
1977: Geological mapping of the Snelgrove Lake–Andre Lake area, Labrador Trough. *In* Report of Activities. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-1, pages 71-78.

1979a: Geology of the eastern margin of the Labrador Trough. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-9, 22 pages.

1979b: Sandgirt–Gabbro Lake Area, scale 1:100,000. Newfoundland Department of Mines and Energy, Mineral Development Division, Map (with marginal notes) 7917.

1987: Platinum-group-element potential in Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 211-224.

Wardle, R.J., Ryan, B. and Ermanovics, I.
In press,a: The eastern Churchill Province, Torngat and New Quebec orogens: an overview. Geoscience Canada, pages 217-222.

Wardle, R.J. and Bailey, D.G.
1981: Early Proterozoic sequences in Labrador. *In* Proterozoic Basins of Canada, supplement. *Edited by* F.H.A. Campbell. Geological Survey of Canada, Paper 81-10 pages 331-358.

Wardle, R.J. and Wilton, D.
1985: Reconnaissance sampling for precious metals in the Kaipokok Bay–Big River area, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Lab 679, 17 pages.

1988: Reconnaissance studies in the Seal Lake–Letitia Lake area, Labrador. *In* Report of Activities, Newfoundland Department of Mines and Energy, Mineral Development Division, pages 35-36.

Wardle, R.J., Ryan, B., Nunn, G.A.G. and Mengel, F.
In press,b: Labrador segment of the Trans-Hudson Orogen: crustal development through oblique convergence and collision. *In* The Trans-Hudson Orogen of North America: Lithotectonic Correlations and Evolution. *Edited by* J. Lewry and M. Stauffer. Geological Association of Canada, Special Paper 37.

Wheeler, E.P. II
1960: Anorthosite-adamellite complex of Nain, Labrador. Bulletin of Geological Society of America, Volume 71, pages 1755-1762.

White, M.V.W. and Martin, R.F.
1980: The metasomatic changes that accompany uranium mineralization in the nonorogenic rhyolites of the Upper Aillik Group, Labrador. Canadian Mineralogist, Volume 18, pages 459-479.

Wilton, D.H.C.
1988: Copper occurrences in the Bruce River Group, Labrador, Central Mineral Belt. *In* Current Research, Part C. Geological Survey of Canada, Report 88-1C, pages 291-297.

1989a: Studies in the Seal Lake Group, central Labrador, Part I: Description of copper occurrences. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 23-34.

1989b: Studies in the Seal Lake Group, central Labrador, Part II: geochemistry of diabase sills. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 35-46.

In press: Metallogeny of the Labrador Central Mineral Belt. Geological Survey of Canada.

Wilton, D.H.C., MacDougall, C.S., MacKenzie, L.M. and North, J.W.
1987: Precious metal contents in samples from the eastern Central Mineral Belt. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Lab 724, 46 pages.

Wilton, D.H.C. and Wardle, R.H.
1987: Two contrasting metallogenic styles in the Early Proterozoic Upper Aillik Group, Central Mineral Belt, Labrador, Canada. Mineralium Deposita, Volume 22, pages 198-207.

1990: Geological reconnaissance survey of northernmost Labrador. *In* Report of Activities, 1990. Newfoundland Department of Mines and Energy, Geological Survey Branch, pages 15-18.

Wynne-Edwards, H.R. and Hasan, Z.-U.
1970: Intersecting orogenic belts across the North Atlantic. American Journal of Science, Volume 268, pages 289-308.

Zajac, I.S.
1974: The stratigraphy and mineralogy of the Sokoman Formation in the Knob Lake area, Quebec, and Newfoundland. Geological Survey of Canada, Bulletin 220, 159 pages.

Zajac, I.S., Miller, R.R. and Nantel, S.
1984: Le gite de Zr, Y, Nb et Be du complex alcalin de Strange Lake, Quebec-Labrador. Quebec Ministere de l'Energie et des Ressources, DV 85-18, pages 127-142.

Note: Geological Survey Branch file numbers are included in square brackets.

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 391-393

CORE-STORAGE PROGRAM, 1990

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INTRODUCTION

In 1979, the Newfoundland Department of Mines and Energy started a drill-core collection and storage program. The objective of this ongoing program is to provide well-maintained and representative collections of drill core from as many drilling programs as possible, for the future use of the mineral exploration industry, government, and university geoscientists and other geotechnical professionals.

This report summarizes activities during 1990, and presents an overview of the operations of the core-storage program.

DRILL-CORE ACQUISITION

During 1990, drill-core acquisition continued in insular Newfoundland and in Labrador and 15,944 m of drill-core samples were added to the collection.

Most of these core samples, 11,548 m from 136 drillholes, were selected as representative samples from Newfoundland Zinc Mines at Daniel's Harbour, which ceased production in 1990. Approximately 1,283 m of core samples from the Mine Brook area, Pilley's Island, were also collected.

In Labrador, 2,257 m from 27 drillholes, were collected from Kennco Explorations Limited's 1959 drilling program in the Seal Lake area and are now being stored in the Goose Bay core library, and an additional 857 m of core samples from the Central Mineral Belt were added to our collection.

In total, approximately 691,727 m of drill-core samples are now being stored in buildings operated by the Department of Mines and Energy.

A catalogue of all open core samples in Department core libraries is available from the Publications and Information Section of the Department of Mines and Energy.

DRILL-CORE LIBRARIES

The Department of Mines and Energy now operates six core-storage libraries located at St. John's, Buchans, Springdale, Baie Verte, Pasadena and Goose Bay (Figure 1).

The St. John's library is staffed on a full-time basis except during the field season. It is equipped with a rock saw, a stereomicroscope, a magnetic susceptibility meter, a resistivity meter, an ultraviolet light and a McPhar TV-1 scintillometer.

The Goose Bay core library, which contains core from Labrador, is not staffed on a full-time basis. It has facilities similar to, and shares equipment with, the St. John's core library.

The Pasadena core library is also staffed on a full-time basis. This library has equipment similar to the St. John's library, and is also equipped with a ventilated room for storing radioactive core, and a humidity-controlled room for storing moisture-sensitive core samples. The Pasadena building has reached its capacity with only a little working space made free for new core additions by moving some 'low-priority' core outside the building for continued storage.

Claim tags can be purchased at the Pasadena core library and up-to-date sections of all claim maps are available, on request, through the Pasadena core library through facsimile machine from St. John's. The facility also serves as the summer headquarters for the quarry inspector responsible for the western part of insular Newfoundland and for Labrador.

The Springdale library is operated by the resident Pasadena geologist from the Pasadena core library, on an appointment basis only. It has a core splitter and a rock saw but shares other geotechnical instruments with the Pasadena core library.

The Buchans core library contains core samples from drilling done by ASARCO and Abitibi-Price during the years these companies were active in mining and mineral exploration in Buchans and surrounding areas. The construction of an office/core examination area was completed in 1990 and this building is now fully operational. Drillhole logs, location maps and other data on core in the Buchans library are being stored in Pasadena and all visits to the Buchans core library are being handled by staff from the Pasadena core library on an appointment basis.

The Baie Verte core-storage building is now partially operational. Construction of core-storage racks having a capacity of approximately 5,000 boxes of BQ size core has been completed. Renovations to the office area in this building are scheduled for completion in the winter of 1991 and this

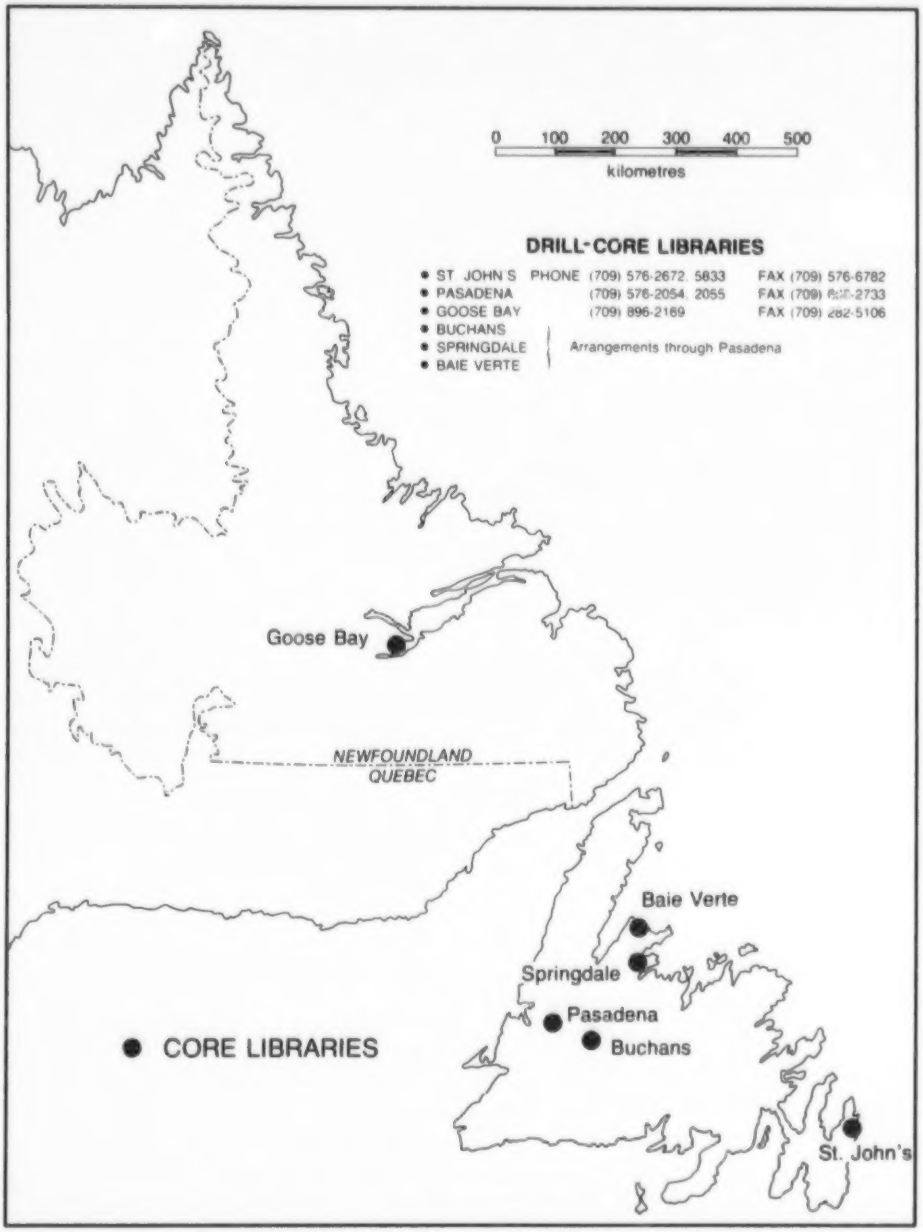

0 100 200 300 400 500
kilometres
DRILL-CORE LIBRARIES
● ST. JOHN'S PHONE (709) 576-2672, 5833 FAX (709) 576-6782
● PASADENA (709) 576-2054, 2055 FAX (709) [illegible]-2733
● GOOSE BAY (709) 896-2169 FAX (709) 282-5106
● BUCHANS
● SPRINGDALE
● BAIE VERTE
Arrangements through Pasadena
Goose Bay
NEWFOUNDLAND
QUEBEC
Baie Verte
Springdale
Pasadena
Buchans
St. John's
● CORE LIBRARIES

Figure 1. *Core libraries in Newfoundland and Labrador.*

facility will be fully operational as soon as construction is completed. This core library will also be operated from Pasadena.

INFORMATION FILES

The St. John's office and the Pasadena core library now have microcomputers to assist in searching the core-sample holdings and to search datafiles kept on core samples in the core libraries.

Two datafiles are currently available for searches in Pasadena and St. John's. One file contains the drillhole index data, parts of which are used to compile the drillhole catalog; the other file contains a summary of all assays conducted on core samples stored in our core libraries, excluding Buchans. Both files have been combined in OPEN FILE NFLD 1889, available from the Publications and Information Section of the Department of Mines and Energy.

CONFIDENTIAL STORAGE

The Department discontinued the practice of confidential storage of industry core samples in November of 1989. All new samples that are added to our core collections are now open and available for inspection by interested parties.

ACCESS TO CORE LIBRARIES

The Department now operates six core-storage libraries and has fulltime staff assigned to only the St. John's and Pasadena facilities. Visits to all core libraries should be arranged several days in advance to ensure that staff can properly accommodate all persons wishing to make use of the core storage facilities.

The contact people are Alvin Harris, St. John's, 576-5833 and Stewart Cochrane, Pasadena, 686-2054.

*Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 395-397*

MINERAL OCCURRENCE DATA SYSTEM

C.F. O'Driscoll, J. Smith, G. Stapleton and D. King
Mineral Deposits Section

The Mineral Occurrence Data System (MODS) is a two-part project, which consists of a manual Mineral Inventory File and a computerized Mineral Index. The project is designed to offer an efficient information service on all the mineral occurrences in Newfoundland and Labrador.

The Mineral Inventory File is part of the National Mineral Inventory and consists of mineral-occurrence descriptions that summarize all data on known mineral occurrences in the province. The file presently contains approximately 4000 descriptions, including all mineral occurrences for the Island of Newfoundland (Figure 1) and selected areas in Labrador (Figure 2). The file and topographic location maps have been microfiched and duplicates are available upon request.

At present, the Mineral Inventory File for the Island of Newfoundland is being updated. This file was started in 1978, and since then, much new geological mapping and exploration have been carried out and many new occurrences have been discovered. Updates were done in the past only on land tenure and major mineral occurrences. Areas that have been updated with new mineral-occurrence descriptions include major parts of 12A, 12B and 12H map areas. In addition, industrial minerals for all of Newfoundland have been documented.

Mineral-occurrence maps that have updated geological bases have been published at a 1:250,000 scale and are available upon request. In addition, selected areas have been published at 1:50,000 and 1:100,000 scales. These maps contain locations, a listing and a brief description of the occurrences. An industrial minerals map of the Island of Newfoundland is in the final stages of preparation.

The computerized Mineral Index contains information selectively extracted from the Mineral Inventory File, which is stored on a Hewlett Packard 9000/560 Unix-operated mini computer, located at the Geological Survey Branch, Department of Mines and Energy, 95 Bonaventure Avenue, St. John's. The Geological Retrieval and Synopsis Program (GRASP) developed by the United States Geological Survey is used to manage and manipulate the database. GRASP permits users to perform complex searches of the mineral inventory data. The database presently contains information on approximately 3700 mineral occurrences. This database is being published on floppy disk along with a database program, which will enable users to install the database on their personal computers (see Stapleton *et al.*, *this volume*).

An index to the province's industrial mineral occurrences is also available. This database utilizes IBM compatible REFLEX software stored on a H.P. Vectra ES/12 micro computer and provides a quick index to industrial mineral occurrences. Users interested in a particular commodity can retrieve a listing of that commodity's occurrences, thus simplifying their search of the manual file.

The manual Mineral Inventory File is used as a quick reference to specific deposits. Exploration-company personnel frequently request information on a particular mineral showing or prospect. This is particularly true of those companies new to the province or those moving into new areas. Generally, this preliminary research is done at the Department of Mines and Energy by government personnel. However, since a large part of the file has been microfiched, it is available to all companies at a reasonable cost.

The Mineral Inventory File is used daily by government geologists in land-use planning. Advice is given to various departments of government in establishing wilderness areas, hydro developments, provincial and national parks, and any other developments that may conflict with future mineral exploration and development. In addition, municipal councils and the Department of Municipal Affairs are advised of the location, extent, and nature of mineral deposits in specific areas, so that new housing and commercial developments, municipal parks, water reservoirs and sewage-disposal systems can be located, where possible, in areas of low mineral potential.

Copies of the file are made available to the various agencies of the federal government such as the Mineral Policy Sector and the Geological Survey of Canada. These are then adapted to the National Mineral Inventory, MINSYS and CANMINDEX.

The file is available to anyone who is researching mineral deposits in the province. It is useful to students who are writing papers on specific mineral deposits and to company and government personnel who are writing proposals for future work, or preparing information brochures about particular areas.

Using computers, the retrieval capability of the Mineral Index is optimized and complex retrievals can be made that would be virtually impossible if a manual system were used.

REFERENCE

Stapleton, G., Parsons, W.K., O'Driscoll, C.F., King, D. and Smith, J.
This volume: A mineral deposit database for microcomputers.

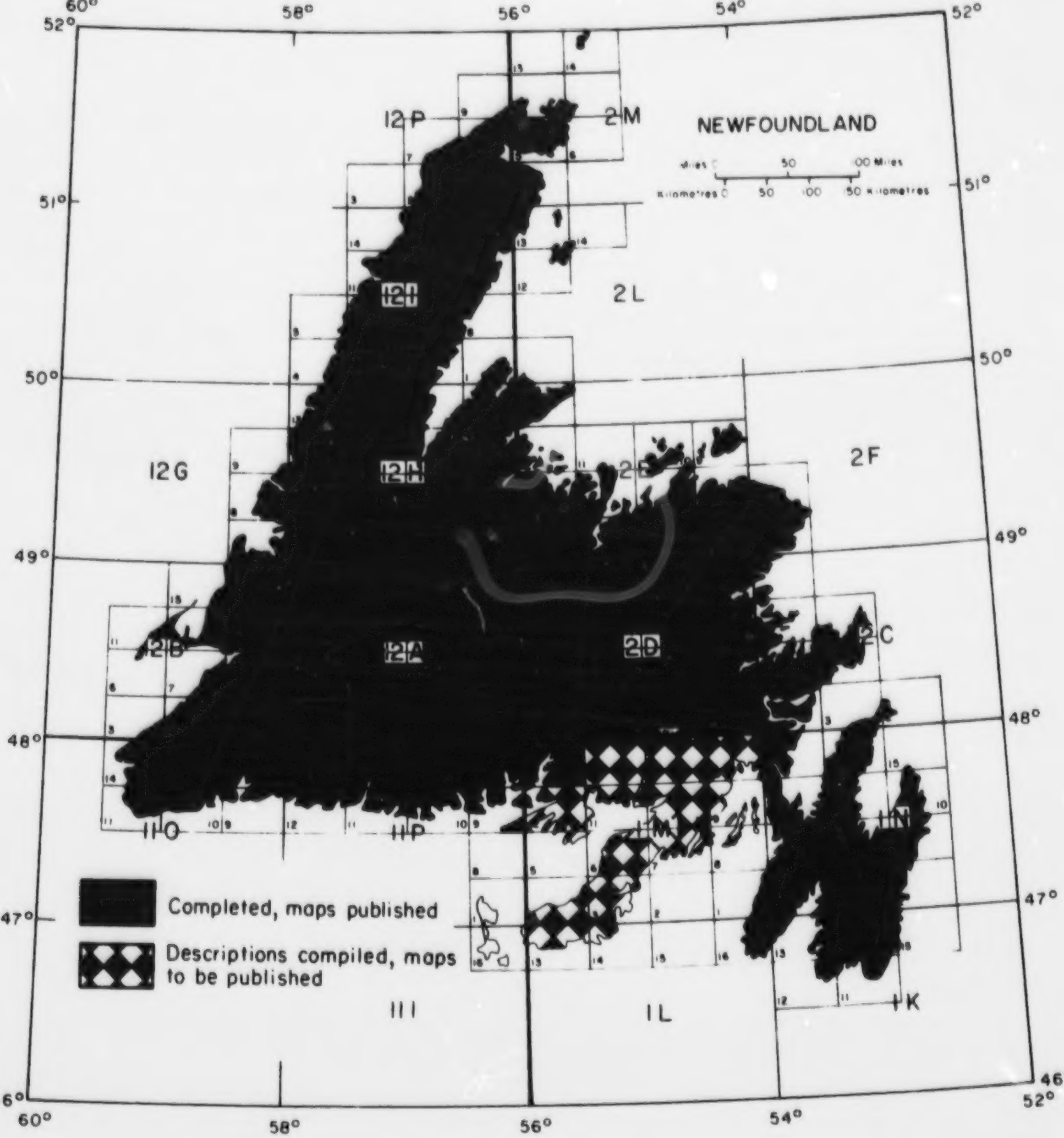
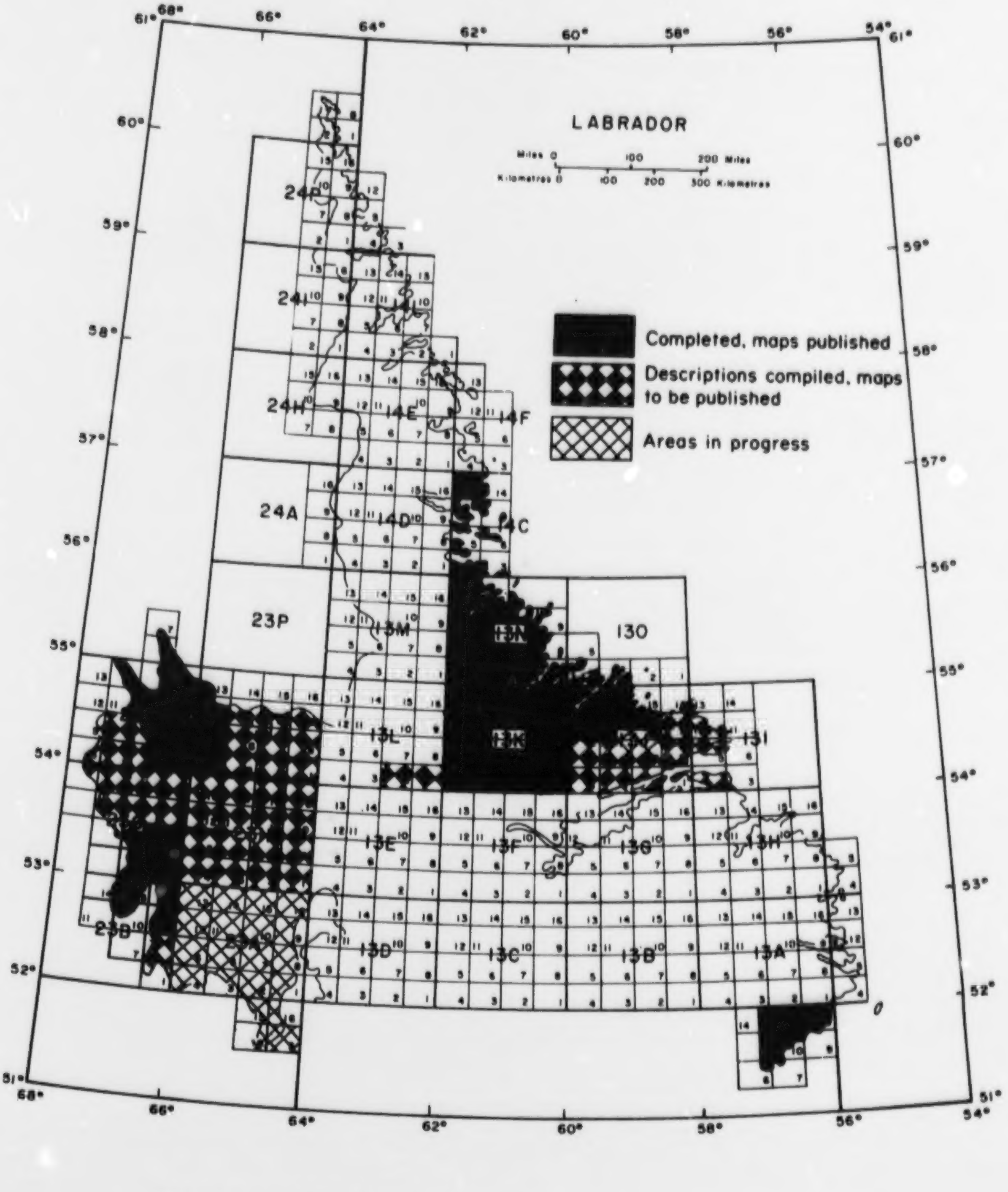

NEWFOUNDLAND
Miles 0 50 100 Miles
Kilometres 0 50 100 150 Kilometres
60°
58°
56°
54°
52°
52°
51°
50°
49°
48°
47°
46°
12P
2M
2L
12I
12H
12G
2E
2F
12A
2D
12B
2C
11O
11P
1M
1N
11I
1L
1K
Completed, maps published
Descriptions compiled, maps to be published

Figure 1. *Index map for Mineral Occurrence Data System project, insular Newfoundland.*


LABRADOR
Miles 0 100 200 Miles
Kilometres 0 100 200 300 Kilometres
Completed, maps published
Descriptions compiled, maps to be published
Areas in progress
24P
24I
24H
24A
23P
23B
23A
14E
14F
14D
14C
13M
13O
13L
13I
13E
13F
13G
13H
13D
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55°
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53°
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51°

Figure 2. *Index map for Mineral Occurrence Data System project, Labrador.*

Current Research (1991) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, page 399

GEOSCAN–THE NATIONAL DATABASE FOR GEOLOGICAL INFORMATION: THE NEWFOUNDLAND CONTRIBUTION

Catherine Patey and Janet Gillespie
Publications and Information Section

GEOSCAN is a computerized bibliographic database of Canadian-produced and/or Canada-related geoscience documents.

The Department of Mines and Energy, Government of Newfoundland and Labrador, is one of sixteen agencies that index documents into this national database. The departmental files, including mineral assessment reports, mineral inventory cards, published reports and maps, university theses, etc., are the sources of the indexed records. Additional documents, produced and edited by related agencies, e.g., the Geological Survey of Canada, are the source of other indexed records referring to this province.

Since the conversion of the database to the MINISIS software system in 1982, about 1200 records of mineral assessment files have been added to the database, although other types of documents, in particular, those for government publications, have also been indexed. From May 1990, all additional records are batched into GEOSCAN via Datapac.

Besides indexing and keying new records, improved keying and editing procedures are being developed with WordPerfect 5.0 macros, and new coding sheets are being produced. The authority files and thesauri used in coding are being enlarged, and all the terms used are being more clearly defined. These terms are maintained on various card files and binders, e.g., company name card file, mineral lands information card file, drillhole information binder, etc. The information on these card files and binders is being transferred to several mini databases on CDS/ISIS and Reflex II software for easier access and reference. These files and mini databases help to make indexing consistent and are also useful for in-house inquiries.

As of November 1990, there were 140,400 records in the database, including 9600 referring to this province. The non-confidential records are available through on-line computer searches at the Geological Survey of Canada Library in Ottawa, and at the Publications and Information Section of the Geological Survey Branch in St. John's. The number of requested searches has more than doubled in the past year.

References to documents referring to the geoscience of this province are also available from various printed GEOSCAN Newfoundland and Labrador indices:

1. Indices to documents (including those authored by the Geological Survey of Canada) referring to this province with records in the database up to February 1982 are:

   −sorted by NTS−National Topographic System
   −sorted by Keywords
   −sorted by Author (both corporate and personal)

2. Computer printout to mineral-assessment-file records entered into the database during the period 1982-1984 are:

   −sorted by NTS

3. Index to mineral-assessment-file records received by the Publications and Information Section during the period April 1985 to June 1988 (272 records) are:

   −sorted by NTS
   −sorted with cross-reference lists by company name, release date, geographic area, local Geofile number.

4. Index to mineral-assessment-file records received by the Publications and Information Section during the period July 1988 to June 1989 (Open File Nfld/1927) (628 records) are:

   −sorted by NTS
   −sorted with cross-reference lists as above.

A similar NTS index to mineral assessment files, received during the period July 1989 to June 1990 (Open File Nfld/2068) (292 records) is also available.

We welcome suggestions for improvements and appreciate being notified of any errors or discrepancies in the earlier indices. For further information on GEOSCAN, please contact Catherine Patey (709) 576-6441.

Current Research (1991) Newfoundland Department of Mines and Energy,
Geological Survey Branch, Report 91-1, pages 401-403

A MINERAL DEPOSIT DATABASE FOR MICROCOMPUTERS

G. Stapleton, W.K. Parsons[1], C.F. O'Driscoll, D. King and J. Smith
Mineral Deposits Section

ABSTRACT

Mods/PC is a menu-driven program for IBM-compatible microcomputers that provides the user with access to the computerized mineral inventory system. The MODS database presently contains information on approximately 4000 metallic, non-metallic, fossil fuel, rare-earth element and radioactive mineral deposits. Each mineral deposit is described by a single MODS record, which has fifty-nine information fields. More detailed information on the deposit can be obtained by consulting key references listed in each record or by examining the hard copy mineral inventory reports maintained at the Geological Survey Branch, 95 Bonaventure Avenue, St. John's, Newfoundland.

INTRODUCTION

The Mineral Deposit Database for microcomputers represents the most recent step in the evolution of the Geological Survey Branch's Mineral Occurrence Data System (MODS).

The Mineral Occurrence Data System (Figure 1) initially began in 1971 as a manual Mineral Inventory File. It consisted of very brief data recorded on 8- by 11-inch cards for each mineral occurrence and a series of topographic maps showing locations (Hsu, 1974). In 1976, a folio of mineral occurrence maps was published at a scale of 1:250,000. These were accompanied by a booklet of mineral occurrence tables (Douglas, 1976a, b) that contained very brief descriptions compiled from the Mineral Inventory File.

In 1978, the system underwent a major revision. The information contained on mineral inventory cards was greatly increased so that presently, there is a summary report on each occurrence. Location maps having geological bases were systematically compiled and published at 1:250,000 scale (some at 1:100,000 and 1:50,000).

At the same time (1978), the computerization of MODS began. The data record was defined and the Geological Retrieval and Synopsis Program (GRASP) was chosen as the database program (Missan *et al.*, 1979). GRASP was developed by the United States Geological Survey (Bowen and Botbol, 1975) as a geological storage and retrieval system to be used primarily by geologists. The computerized MODS system first resided on an IBM 370/158 (MVS) located at Newfoundland and Labrador Computer Services and was accessed by a high-speed terminal from the Department of Mines and Energy.

In 1987, the computerized MODS database and GRASP were ported to a Hewlett Packard 9000/560 Unix-operated minicomputer located at the Geological Survey Branch of the Department of Mines and Energy. It was found that this in-house database system did not serve industry very well, as a visit to the Geological Survey Branch was necessary in order to gain access.

DEVELOPMENT OF MODS/PC

With the proliferation of microcomputers and the need for easier access to MODS information, it was decided to develop a microcomputer version of this information system in 1990. The Mineral Occurrence Data System microcomputer application (MODS/PC V1.0) was written in-house by W. Keith Parsons, Systems Analyst with the Department of Mines and Energy. It was written in the R:Base Database language (V2.11) and compiled using the R:Base compiler (V1.02). R:Base was chosen as the development tool because of the program's support of long string fields and the availability of a vendor-supplied compiler.

The minimum system requirements needed to run the MODS/PC program include an IBM-compatible microcomputer with an 80286 processor, 640 K of RAM, a hard disk, and a CGA videocard/monitor. As well, the system must have at least 475 K of free memory. To achieve this, certain memory resident programs may have to be deactivated.

The MODS/PC system is distributed on four 5¼" diskettes in a compressed format. An installation program (install.exe) aids the user in setting up the system by checking the target microcomputer's parameters, copying files to the hard disk, and uncompressing these files. PKZIP, the industry standard compression utility distributed by PKware Inc., is

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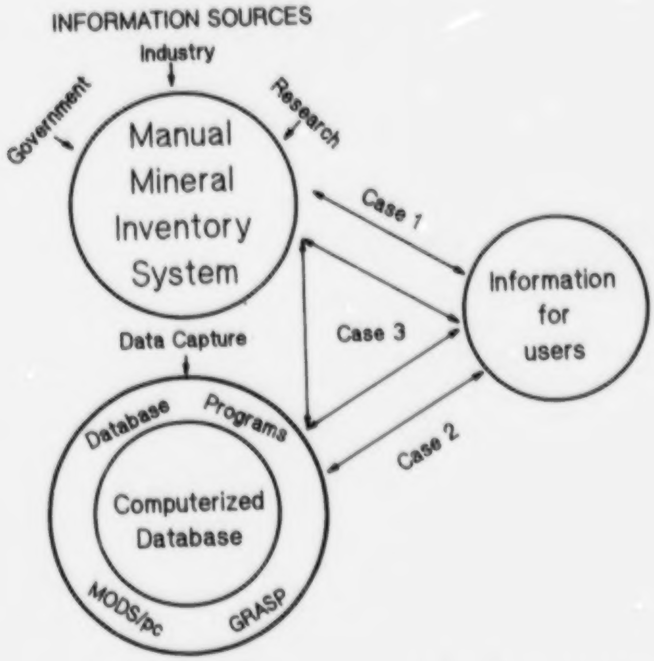
[1] Computer Unit


INFORMATION SOURCES
Industry
Government
Research
Manual Mineral Inventory System
Case 1
Information for users
Case 3
Data Capture
Database
Programs
Computerized Database
MODS/pc
GRASP
Case 2

The Mineral Occurrence Data System can be used in three ways.

Case 1: The user wants detailed information on a specific mineral occurrence or group of mineral occurrences in a specific area. This information can be retrieved quickly using the manual mineral inventory file.

Case 2: The user wants less detailed information on all occurrences of a particular type, ie. vein type, located over a large geographic area. The computerized mineral deposits database can provide this information in printout format along with a computer generated location map.

Case 3: The user wants detailed comprehensive information on all occurrences of several types over a large geographic area. The purpose being to access the regions mineral potential and hopefully zero in on an area for field investigation and staking. In this case the computerized mineral deposits database is searched and used to narrow down and define specific occurrences or areas of interest. The more detailed manual mineral inventory reports can then be provided. The user can then use references contained in the manual reports to locate other information sources.

Figure 1. *Sketch illustrating how MODS is used.*

used to compress the MODS/PC system. However, possession of this software is unneccessary as the files are in a self-extracting executable format. The compression ratio is better than ten to one so considerable hard disk space is required.

Only one data set may be installed at a time. The user may select between Newfoundland occurrences (2566 records occupying 6.1 mb.), Labrador occurrences (1259 records occupying 3.0 mb.) or a demonstration dataset (164 records occupying 420 K). The program itself occupies about 400 K of hard disk space.

The MODS/PC program is menu-driven and provides the user with complete access to the computerized Mineral Occurrence Data System. The program allows the user to search, view and output occurrences from the database. Custom designed searches are achieved by setting conditions and using Boolean logic to combine these conditions in different ways. Data portability is provided by the ability to write data to an ASCII delimited file. This allows input of a user-selected dataset to other application programs such as spreadsheets and databases or portability to other types of computer systems such as non-DOS microcomputers, minicomputers, or even mainframes. Full user documentation will be supplied with the program.

The MODS database, which is primarily designed as an index to the mineral deposits and occurrences of Newfoundland and Labrador, contains information on approximately 4000 metallic, non-metallic, fossil fuel, rare-earth element and radioactive mineral deposits. Rocks used for their chemical properties or building stone are also included.

Each mineral deposit is described by a single MODS record, which has fifty-nine information fields. More detailed information on the deposit can be obtained by consulting key references listed in each record or by examining the hard copy mineral inventory reports maintained at the Geological Survey Branch, 95 Bonaventure Avenue, St. John's, Newfoundland. These reports will allow information to be traced back to its source publication.

Most of the MODS information was compiled by a systematic search of mineral exploration company assessment files. Other sources of information included publications of the Newfoundland Department of Mines and Energy, the Geological Survey of Canada, news items from the press, publications in geological and mining journals, and personal communications from mining-company and government personnel.

Version 1.0 of the MODS/PC system will be released to the public by April, 1991. Periodically, upgrades to the system will be made available to the user. Subsequent releases will update the current records, add new occurrences, and provide revisions to the program. The MODS/PC program will be upgraded to version 3.1 of R:Base once a new compiler is released by Microrim Inc. The revisions will produce a modernized user interface, faster access times, and improved report generation. The R:Base compiler produces object files compatible with common 3rd-generation languages such as C. Future versions of MODS/PC may make use of this ability to add graphical options such as plotting and mapping to the program.

In the future, when optical disk technology becomes widely used, it is planned to release all of the MODS reports on optical disk. This will enable subscribers to have the entire Mineral Occurrence Data System, including maps, MODS/PC and reports, in-house.

REFERENCES

Bowen, R.W. and Botbol, J.M.
1975: The geological retrieval and synopsis program (GRASP). United States Geological Survey, Professional Paper 966, 87 pages.

Douglas, C.
1976a: Mineral occurrence tables, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Lab. 326, 94 pages.

1976b: Mineral occurrence tables, Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Nfld. 888, 98 pages.

Hsu, E.
1974: Mineral inventory. *In* Report of Activities. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 73-1, pages 6-8.

Missan, H.S., McArthur, J.G. and Andrews, K.
1979: MODS—Mineral occurrence data system. *In* Report of Activities. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 79-1, pages 182-196.

ERRATUM

Figure 5 of "Geology of Grenville Province crystalline rocks in the region between Wilson and Winokapau lakes (NTS 13E/1, 13E/2, 13E/7 and 13E/8), south-central Labrador", by A. Thomas and P. Blomberg (Current Research, Report 90-1), was incorrectly constructed. The authors and publishers apologize for any confusion this inadvertent error may have caused. The correct figure is given below.

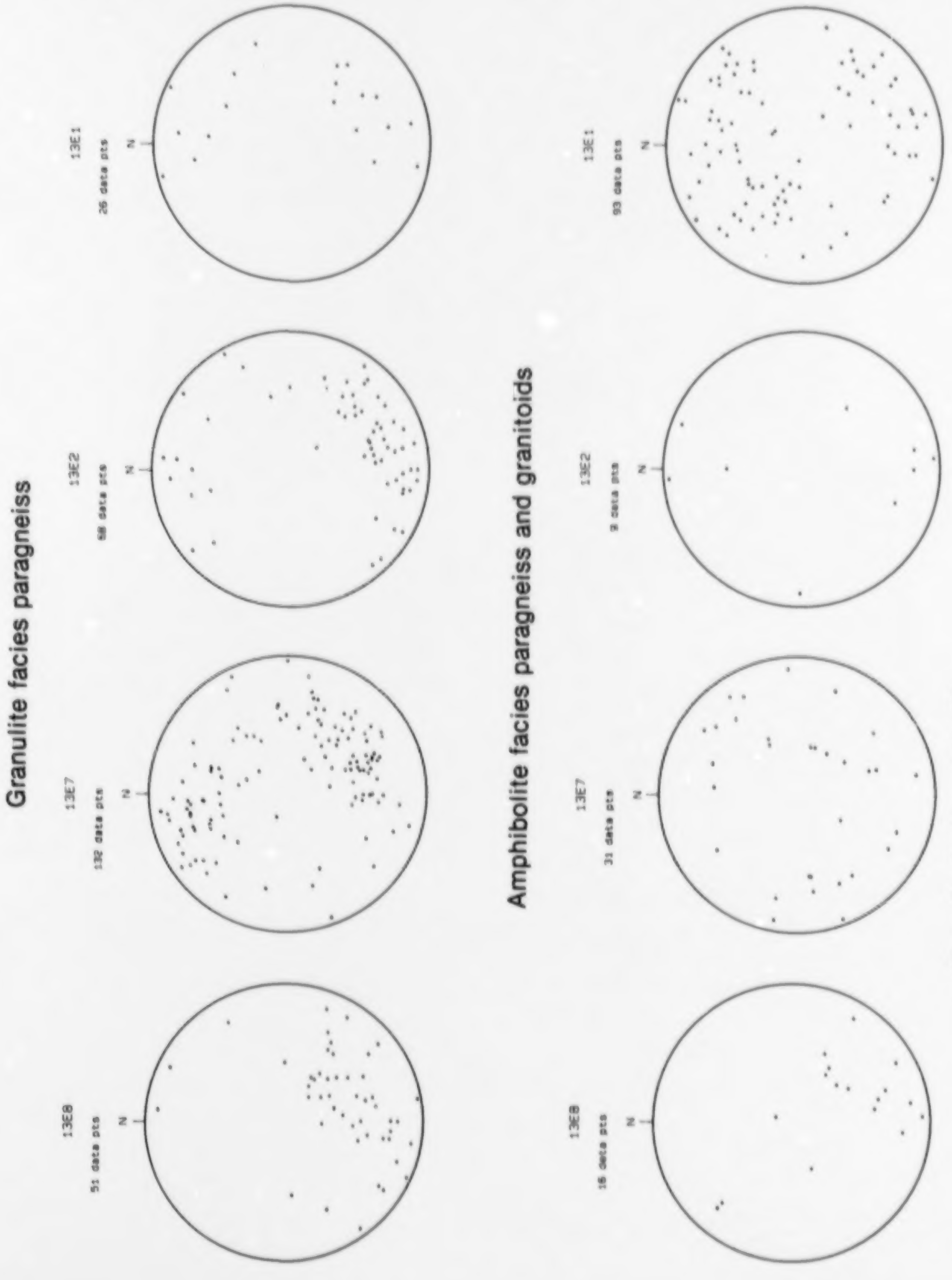


Figure 5. *Caption on page 405.*

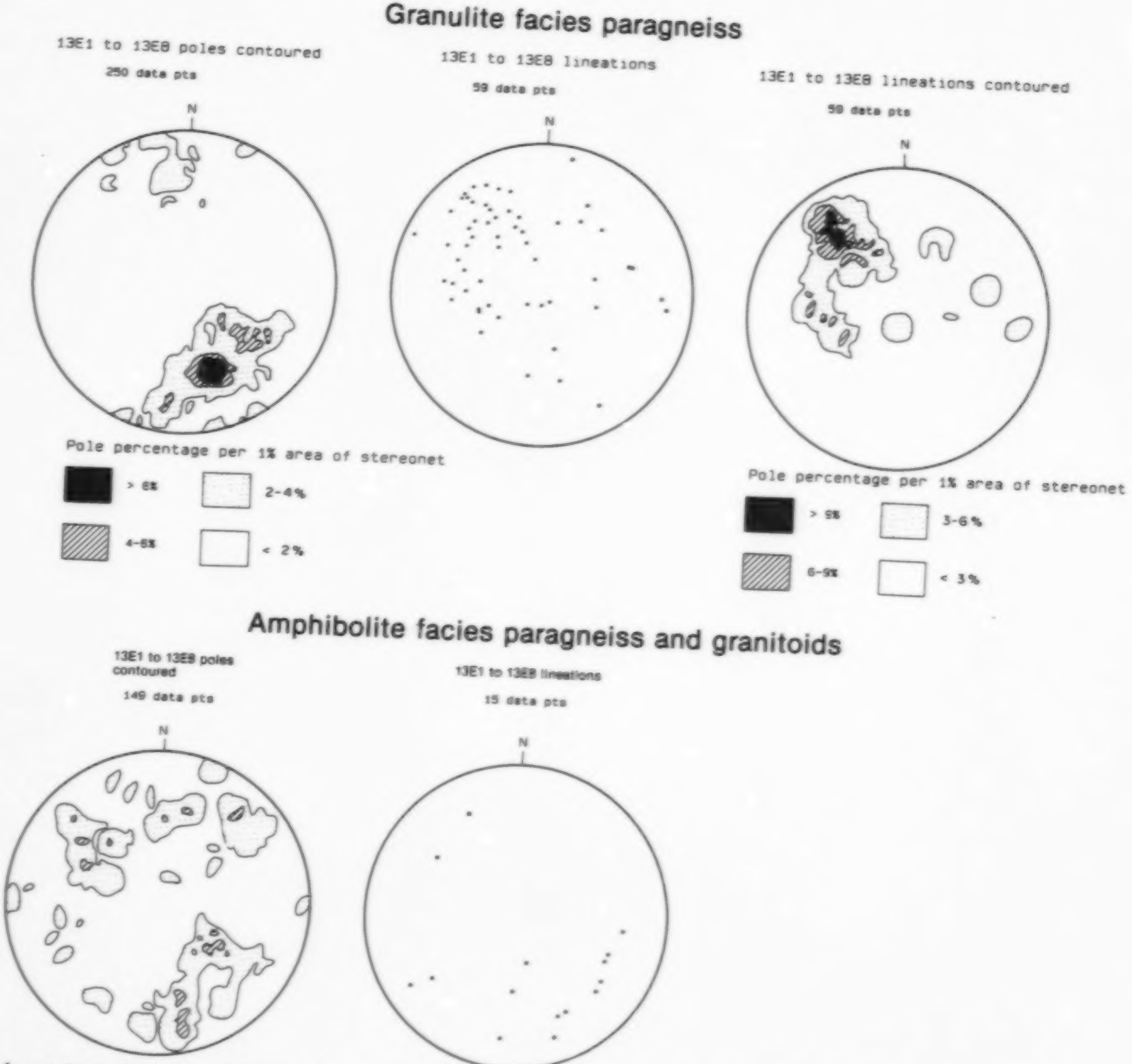


Figure 5. *Equal area, lower hemisphere Schmidt net stereographic plots of poles to gneissic banding/foliation planes and of lineation data for the region between Wilson and Winokapau lakes.*